# INFLUENZA VIRUS VACCINES AND USES THEREOF

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## 1. INTRODUCTION

**[0002]** Provided herein are chimeric influenza virus hemagglutinin polypeptides and compositions comprising the same, vaccines comprising the same, and methods of their use.

## 2. BACKGROUND

**[0003]** Influenza viruses are enveloped RNA viruses that belong to the family of Orthomyxoviridae (Palese and Shaw (2007) Orthomyxoviridae: The Viruses and Their Replication, 5th ed. Fields' Virology, edited by B.N. Fields, D.M. Knipe and P.M. Howley. Wolters Kluwer Health/Lippincott Williams & Wilkins, Philadelphia, USA, p1647-1689). The natural host of influenza A viruses are mainly avians, but influenza A viruses (including those of avian origin) also can infect and cause illness in humans and other animal hosts (bats, canines, pigs, horses, sea mammals, and mustelids). For example, the H5N1 avian influenza A virus circulating in Asia has been found in pigs in China and Indonesia and has also expanded its host range to include cats, leopards, and tigers, which generally have not been considered susceptible to influenza A (CIDRAP - Avian Influenza: Agricultural and Wildlife Considerations). The occurrence of influenza virus infections in animals could potentially give rise to human pandemic influenza strains.

**[0004]** Influenza A and B viruses are major human pathogens, causing a respiratory disease that ranges in severity from sub-clinical infection to primary viral pneumonia which can result in death. The clinical effects of infection vary with the virulence of the influenza strain and the exposure, history, age, and immune status of the host. The cumulative morbidity and mortality caused by seasonal influenza is substantial due to the relatively high attack rate. In a normal season, influenza can cause between 3-5 million cases of severe illness and up to 500,000 deaths worldwide (World Health Organization (2003) Influenza: Overview; March 2003). In the United States, influenza viruses infect an estimated 10-15% of the population (Glezen and Couch RB

(1978) Interpandemic influenza in the Houston area, 1974-76. N Engl J Med 298: 587-592; Fox *et al.* (1982) Influenza virus infections in Seattle families, 1975-1979. II. Pattern of infection in invaded households and relation of age and prior antibody to occurrence of infection and related illness. Am J Epidemiol 116: 228-242) and are associated with approximately 30,000 deaths each year (Thompson WW *et al.* (2003) Mortality Associated with Influenza and Respiratory Syncytial Virus in the United States. JAMA 289: 179-186; Belshe (2007) Translational research on vaccines: influenza as an example. Clin Pharmacol Ther 82: 745-749).

**[0005]** In addition to annual epidemics, influenza viruses are the cause of infrequent pandemics. For example, influenza A viruses can cause pandemics such as those that occurred in 1918, 1957, 1968, and 2009. Due to the lack of pre-formed immunity against the major viral antigen, hemagglutinin (HA), pandemic influenza can affect greater than 50% of the population in a single year and often causes more severe disease than epidemic influenza. A stark example is the pandemic of 1918, in which an estimated 50-100 million people were killed (Johnson and Mueller (2002) Updating the Accounts: Global Mortality of the 1918-1920 "Spanish" Influenza Pandemic Bulletin of the History of Medicine 76: 105-115). Since the emergence of the highly pathogenic avian H5N1 influenza virus in the late 1990s (Claas *et al.* (1998) Human influenza A H5N1 virus related to a highly pathogenic avian influenza virus. Lancet 351: 472-7), there have been concerns that it may be the next pandemic virus. Further, H7 and H9 strains are candidates for new pandemics since these strains infect humans on occasion.

**[0006]** An effective way to protect against influenza virus infection is through vaccination; however, current vaccination approaches rely on achieving a good match between circulating strains and the isolates included in the vaccine. Such a match is often difficult to attain due to a combination of factors. First, influenza viruses are constantly undergoing change: every 3-5 years the predominant strain of influenza A virus is replaced by a variant that has undergone sufficient antigenic drift to evade existing antibody responses. Isolates to be included in vaccine preparations must therefore be selected each year based on the intensive surveillance efforts of the World Health Organization (WHO) collaborating centers. Second, to allow sufficient time for vaccine manufacture and distribution, strains must be selected approximately six months prior to the initiation of the influenza season. Often, the predictions of the vaccine strain selection committee are inaccurate, resulting in a substantial drop in the efficacy of vaccination.

**[0007]** The possibility of a novel subtype of influenza A virus entering the human population also presents a significant challenge to current vaccination strategies. Since it is impossible to predict what subtype and strain of influenza virus will cause the next pandemic, current, strain-specific approaches cannot be used to prepare a pandemic influenza vaccine.

## 3. SUMMARY

**[0008]** In one aspect, provided herein are chimeric influenza hemagglutinin (HA) polypeptides that induce a cross-protective immune response against the conserved HA stem domain of influenza viruses. The chimeric influenza HA polypeptides provided herein comprise a stable (e.g., properly formed) HA stem domain and a globular HA head domain that is heterologous to the stem domain (i.e. the head and stem domains are derived from different strains and/or subtypes of influenza virus).

**[0009]** In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide provided herein comprises (i) the stem domain of the hemagglutinin from an influenza virus of the H1 subtype and (ii) the globular head domain of the hemagglutinin from an influenza virus of the H5 subtype (sometimes referred to herein as a "cH5/1 chimeric influenza hemagglutinin polypeptide"). In a specific embodiment, the stem domain of a cH5/1 chimeric influenza hemagglutinin polypeptide is the stem domain of A/California/4/2009 (H1N1) HA (or the stem domain of an A/California/4/2009-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/1 chimeric influenza hemagglutinin polypeptide is the stem domain of A/California/4/2009 (H1N1) HA (or the stem domain of an A/California/4/2009-like influenza virus HA) and the globular head domain of the cH5/1 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA (or the globular head domain of an A/Vietnam/1203/2004 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/1 chimeric influenza hemagglutinin polypeptide is the stem domain of A/California/4/2009 (H1N1) HA (or the stem domain of an A/California/4/2009-like influenza virus HA) and the globular head domain of the cH5/1 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA (or the globular head domain of an A/Indonesia/5/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/1 chimeric influenza hemagglutinin polypeptide is the stem domain of A/California/4/2009 (H1N1) HA (or the stem domain of an

A/California/4/2009-like influenza virus HA) and the globular head domain of the cH5/1 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA (or the globular head domain of an A/Anhui/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/1 chimeric influenza hemagglutinin polypeptide is the stem domain of A/California/4/2009 (H1N1) HA (or the stem domain of an A/California/4/2009-like influenza virus HA) and the globular head domain of the cH5/1 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA (or the globular head domain of an A/bar headed goose/Quinghai/1A/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/1 chimeric influenza hemagglutinin polypeptide is the stem domain of A/California/4/2009 (H1N1) HA (or the stem domain of an A/California/4/2009-like influenza virus HA) and the globular head domain of the cH5/1 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA (or the globular head domain of an A/turkey/Turkey/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/1 chimeric influenza hemagglutinin polypeptide is the stem domain of A/California/4/2009 (H1N1) HA (or the stem domain of an A/California/4/2009-like influenza virus HA) and the globular head domain of the cH5/1 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA (or the globular head domain of an A/whooperswan/Mongolia/244/2005 (H5)-like influenza virus HA). In specific embodiments, the stem domain of the hemagglutinin from an influenza virus of the H1 subtype of a cH5/1 chimeric influenza hemagglutinin polypeptide provided herein is from an H1 subtype that the majority of the population is naive to. In certain embodiments, the stem domain of the hemagglutinin from an influenza virus of the H1 subtype of a cH5/1 chimeric influenza hemagglutinin polypeptide provided herein is from an upcoming H1N1 vaccine strain, e.g., the H1N1 vaccine strain in use in the year 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027, 2028, 2029, 2030, 2031, 2032, 2032, 2033, 2034, or 2035.

**[0010]** In a specific embodiment, a cH5/1 chimeric influenza hemagglutinin polypeptide does not comprise the stem domain of A/Puerto Rico/8/34 ("PR8") HA and does not comprise the globular head domain of A/Vietnam/1203/2004 (H5) HA.

**[0011]** In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide provided herein comprises (i) the stem domain of the hemagglutinin from an influenza virus of the H3 subtype and (ii) the globular head domain of the hemagglutinin from an influenza virus of the H5 subtype (sometimes referred to herein as a "cH5/3 chimeric influenza hemagglutinin polypeptide"). In a specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA (or the stem domain of an A/Victoria/361/2011 (H3N2)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA (or the stem domain of an A/Victoria/361/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA (or the globular head domain of an A/Vietnam/1203/2004 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) (or the stem domain of an A/Victoria/361/2011 (H3N2)-like influenza virus HA) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA (or the globular head domain of an A/Indonesia/5/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA (or the stem domain of an A/Victoria/361/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA (or the globular head domain of an A/Anhui/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA (or the stem domain of an A/Victoria/361/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA (or the globular head domain of an A/bar headed goose/Quinghai/1A/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA (or the stem domain of an A/Victoria/361/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza

hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA (or the globular head domain of an A/turkey/Turkey/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA (or the stem domain of an A/Victoria/361/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA (or the globular head domain of an A/whooperswan/Mongolia/244/2005 (H5)-like influenza virus HA).

**[0012]** In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA (or the stem domain of an A/harbor seal/Massachusetts/1/2011 (H3N8)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA (or the stem domain of an A/harbor seal/Massachusetts/1/2011 (H3N8)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA (or the globular head domain of an A/Vietnam/1203/2004 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA (or the stem domain of an A/harbor seal/Massachusetts/1/2011 (H3N8)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA (or the globular head domain of an A/Indonesia/5/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA (or the stem domain of an A/harbor seal/Massachusetts/1/2011 (H3N8)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA (or the globular head domain of an A/Anhui/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA (or the stem domain of an A/harbor seal/Massachusetts/1/2011 (H3N8)-like influenza virus HA) and the globular head

domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bbar headed goose/Quinghai/1A/2005 (H5) HA (or the globular head domain of an A/bar headed goose/Quinghai/1A/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) (or the stem domain of an A/harbor seal/Massachusetts/1/2011 (H3N8)-like influenza virus HA) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA (or the globular head domain of an A/turkey/Turkey/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA (or the stem domain of an A/harbor seal/Massachusetts/1/2011 (H3N8)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA (or the globular head domain of an A/whooperswan/Mongolia/244/2005 (H5)-like influenza virus HA).

**[0013]** In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA (or the stem domain of an A/Indiana/10/2011 (H3N2)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA (or the stem domain of an A/Indiana/10/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA (or the globular head domain of an A/Vietnam/1203/2004 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA (or the stem domain of an A/Indiana/10/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA (or the globular head domain of an A/Indonesia/5/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) (or the stem domain of an A/Indiana/10/2011 (H3N2)-like influenza virus HA) HA and the globular

head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA (or the globular head domain of an A/Anhui/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA (or the stem domain of an A/Indiana/10/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA (or the globular head domain of an A/bar headed goose/Quinghai/1A/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA (or the stem domain of an A/Indiana/10/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA (or the globular head domain of an A/turkey/Turkey/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA (or the stem domain of an A/Indiana/10/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA (or the globular head domain of an A/whooperswan/Mongolia/244/2005 (H5)-like influenza virus HA).

**[0014]** In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA (or the stem domain of an A/Perth/16/2009 (H3N2)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA (or the stem domain of an A/Perth/16/2009 (H3N2)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA (or the globular head domain of an A/Vietnam/1203/2004 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA (or the stem domain of an A/Perth/16/2009 (H3N2)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA (or the

globular head domain of an A/Indonesia/5/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA (or the stem domain of an A/Perth/16/2009 (H3N2)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA (or the globular head domain of an A/Anhui/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA (or the stem domain of an A/Perth/16/2009 (H3N2)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA (or the globular head domain of an A/bar headed goose/Quinghai/1A/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA (or the stem domain of an A/Perth/16/2009 (H3N2)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA (or the globular head domain of an A/turkey/Turkey/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA (or the stem domain of an A/Perth/16/2009 (H3N2)-like influenza virus HA) and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA (or the globular head domain of an A/whooperswan/Mongolia/244/2005 (H5)-like influenza virus HA).

**[0015]** In specific embodiments, the stem domain of the hemagglutinin from an influenza virus of the H3 subtype of a cH5/3 chimeric influenza hemagglutinin polypeptide provided herein is from an H3 subtype that the majority of the population is naive to. In certain embodiments, the stem domain of the hemagglutinin from an influenza virus of the H3 subtype of a cH5/3 chimeric influenza hemagglutinin polypeptide provided herein is from an upcoming H3N2 vaccine strain, e.g., the H3N2 vaccine strain in use in the year 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027, 2028, 2029, 2030, 2031, 2032, 2032, 2033, 2034, or 2035.

**[0016]** In a specific embodiment, a cH5/3 chimeric influenza hemagglutinin polypeptide provided herein does not comprise the globular head domain of A/Vietnam/1203/2004 (H5) HA and does not comprise the stem domain of A/Perth/16/2009 (H3) HA.

**[0017]** In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide provided herein comprises (i) the stem domain of the hemagglutinin from an influenza virus of the H3 subtype and (ii) the globular head domain of the hemagglutinin from an influenza virus of the H7 subtype (sometimes referred to herein as a "cH7/3 chimeric influenza hemagglutinin polypeptide").

**[0018]** In a specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA (or the stem domain of an A/Victoria/361/2011 (H3N2)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA (or the stem domain of an A/Victoria/361/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Netherlands/219/03 (H7) HA (or the globular head domain of an A/Netherlands/219/03 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA (or the stem domain of an A/Victoria/361/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/504/04 (H7) HA (or the globular head domain of an A/Canada/504/04 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA (or the stem domain of an A/Victoria/361/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/444/04 (H7) HA (or the globular head domain of an A/Canada/444/04 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA (or the stem domain of an A/Victoria/361/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/chicken/Jalisco/CPA1/2012 (H7) HA (or the globular head domain of

an A/chicken/Jalisco/CPA1/2012 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA (or the stem domain of an A/Victoria/361/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Alberta/24/2001 (H7) HA (or the globular head domain of an A/mallard/Alberta/24/2001 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA (or the stem domain of an A/Victoria/361/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/rhea/NC/39482/93 (H7) HA (or the globular head domain of an A/rhea/NC/39482/93 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA (or the stem domain of an A/Victoria/361/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Netherlands/12/2000 (H7) HA (or the globular head domain of an A/mallard/Netherlands/12/2000 (H7)-like influenza virus HA).

**[0019]** In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA (or the stem domain of an A/harbor seal/Massachusetts/1/2011 (H3N8)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA (or the stem domain of an A/harbor seal/Massachusetts/1/2011 (H3N8)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Netherlands/219/03 (H7) HA (or the globular head domain of an A/Netherlands/219/03 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA (or the stem domain of an A/harbor seal/Massachusetts/1/2011 (H3N8)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/504/04 (H7) HA (or the globular head domain of an A/Canada/504/04 (H7)-like

influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA (or the stem domain of an A/harbor seal/Massachusetts/1/2011 (H3N8)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/444/04 (H7) HA (or the globular head domain of an A/Canada/444/04 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA (or the stem domain of an A/harbor seal/Massachusetts/1/2011 (H3N8)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/chicken/Jalisco/CPA1/2012 (H7) HA (or the globular head domain of an A/chicken/Jalisco/CPA1/2012 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA (or the stem domain of an A/harbor seal/Massachusetts/1/2011 (H3N8)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Alberta/24/2001 (H7) HA (or the globular head domain of an A/mallard/Alberta/24/2001 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA (or the stem domain of an A/harbor seal/Massachusetts/1/2011 (H3N8)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/rhea/NC/39482/93 (H7) HA (or the globular head domain of an A/rhea/NC/39482/93 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA (or the stem domain of an A/harbor seal/Massachusetts/1/2011 (H3N8)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Netherlands/12/2000 (H7) HA (or the globular head domain of an A/mallard/Netherlands/12/2000 (H7)-like influenza virus HA).

**[0020]** In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA (or the stem domain of an A/Indiana/10/2011 (H3N2)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA (or the stem domain of an A/Indiana/10/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Netherlands/219/03 (H7) HA (or the globular head domain of an A/Netherlands/219/03 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA (or the stem domain of an A/Indiana/10/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/504/04 (H7) HA (or the globular head domain of an A/Canada/504/04 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA (or the stem domain of an A/Indiana/10/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/444/04 (H7) HA (or the globular head domain of an A/Canada/444/04 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA (or the stem domain of an A/Indiana/10/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/chicken/Jalisco/CPA1/2012 (H7) HA (or the globular head domain of an A/chicken/Jalisco/CPA1/2012 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA (or the stem domain of an A/Indiana/10/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Alberta/24/2001 (H7) HA (or the globular head domain of an A/mallard/Alberta/24/2001 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA (or the stem domain of an

A/Indiana/10/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/rhea/NC/39482/93 (H7) HA (or the globular head domain of an A/rhea/NC/39482/93 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA (or the stem domain of an A/Indiana/10/2011 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Netherlands/12/2000 (H7) HA (or the globular head domain of an A/mallard/Netherlands/12/2000 (H7)-like influenza virus HA).

**[0021]** In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA (or the stem domain of an A/Perth/16/2009 (H3N2)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA (or the stem domain of an A/Perth/16/2009 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Netherlands/219/03 (H7) HA (or the globular head domain of an A/Netherlands/219/03 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA (or the stem domain of an A/Perth/16/2009 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/504/04 (H7) HA (or the globular head domain of an A/Canada/504/04 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA (or the stem domain of an A/Perth/16/2009 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/444/04 (H7) HA (or the globular head domain of an A/Canada/444/04 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA (or the stem domain of an A/Perth/16/2009 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/chicken/Jalisco/CPA1/2012 (H7)

HA (or the globular head domain of an A/chicken/Jalisco/CPA1/2012 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA (or the stem domain of an A/Perth/16/2009 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Alberta/24/2001 (H7) HA (or the globular head domain of an A/mallard/Alberta/24/2001 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA (or the stem domain of an A/Perth/16/2009 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/rhea/NC/39482/93 (H7) HA (or the globular head domain of an A/rhea/NC/39482/93 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA (or the stem domain of an A/Perth/16/2009 (H3N2)-like influenza virus HA) and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Netherlands/12/2000 (H7) HA (or the globular head domain of an A/mallard/Netherlands/12/2000 (H7)-like influenza virus HA).

**[0022]** In specific embodiments, the stem domain of the hemagglutinin from an influenza virus of the H3 subtype of a cH7/3 chimeric influenza hemagglutinin polypeptide provided herein is from an H3 subtype that the majority of the population is naive to. In certain embodiments, the stem domain of the hemagglutinin from an influenza virus of the H3 subtype of a cH7/3 chimeric influenza hemagglutinin polypeptide provided herein is from an upcoming H3N2 vaccine strain, e.g., the H3N2 vaccine strain in use in the year 2013, 2014, 2015, 2016, 2017, 2018, 2019, 2020, 2021, 2022, 2023, 2024, 2025, 2026, 2027, 2028, 2029, 2030, 2031, 2032, 2032, 2033, 2034, or 2035.

**[0023]** In a specific embodiment, a cH7/3 chimeric influenza hemagglutinin polypeptide does not comprise the globular head domain of A/mallard/Alberta/24/2001 (H7). In another specific embodiment, a cH7/3 chimeric influenza hemagglutinin polypeptide does not comprise the stem domain of A/Perth/16/2009 (H3).

**[0024]** In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide provided herein comprises (i) the stem domain of the hemagglutinin from an influenza B virus and (ii) the globular head domain of the hemagglutinin from an influenza virus of the H5 subtype (sometimes referred to herein as a "cH5/B chimeric influenza hemagglutinin polypeptide").

**[0025]** In a specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA (or the globular head domain of an A/Vietnam/1203/2004 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA (or the globular head domain of an A/Indonesia/5/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA (or the globular head domain of an A/Anhui/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA (or the globular head domain of an A/bar headed goose/Quinghai/1A/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of

A/turkey/Turkey/1/2005 (H5) HA (or the globular head domain of an A/turkey/Turkey/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA (or the globular head domain of an A/whooperswan/Mongolia/244/2005 (H5)-like influenza virus HA).

**[0026]** In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA (or the globular head domain of an A/Vietnam/1203/2004 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA (or the globular head domain of an A/Indonesia/5/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA (or the globular head domain of an A/Anhui/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA (or the globular head domain of an A/bar headed goose/Quinghai/1A/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of

B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA (or the globular head domain of an A/turkey/Turkey/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA (or the globular head domain of an A/whooperswan/Mongolia/244/2005 (H5)-like influenza virus HA).

**[0027]** In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA (or the globular head domain of an A/Vietnam/1203/2004 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA (or the globular head domain of an A/Indonesia/5/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA (or the globular head domain of an A/Anhui/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA (or the globular

head domain of an A/bbar headed goose/Quinghai/1A/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA (or the globular head domain of an A/turkey/Turkey/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA (or the globular head domain of an A/whooperswan/Mongolia/244/2005 (H5)-like influenza virus HA).

**[0028]** In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA (or the globular head domain of an A/Vietnam/1203/2004 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA (or the globular head domain of an A/Indonesia/5/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA (or the globular head domain of an A/Anhui/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of

B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA (or the globular head domain of an A/bar headed goose/Quinghai/1A/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA (or the globular head domain of an A/turkey/Turkey/1/2005 (H5)-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA) and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA (or the globular head domain of an A/whooperswan/Mongolia/244/2005 (H5)-like influenza virus HA).

**[0029]** In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide provided herein comprises (i) the stem domain of the hemagglutinin from an influenza B virus and (ii) the globular head domain of the hemagglutinin from an influenza virus of the H7 subtype (sometimes referred to herein as a "cH7/B chimeric influenza hemagglutinin polypeptide").

**[0030]** In a specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Netherlands/219/03 (H7) HA (or the globular head domain of an A/Netherlands/219/03 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/504/04 (H7) HA (or the globular head domain of an

A/Canada/504/04 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/444/04 (H7) HA (or the globular head domain of an A/Canada/444/04 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/chicken/Jalisco/CPA1/2012 (H7) HA (or the globular head domain of an A/chicken/Jalisco/CPA1/2012 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Alberta/24/2001 (H7) HA (or the globular head domain of an A/mallard/Alberta/24/2001 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/rhea/NC/39482/93 (H7) HA (or the globular head domain of an A/rhea/NC/39482/93 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Netherlands/12/2000 (H7) HA (or the globular head domain of an A/mallard/Netherlands/12/2000 (H7)-like influenza virus HA).

**[0031]** In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006

HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Netherlands/219/03 (H7) HA (or the globular head domain of an A/Netherlands/219/03 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/504/04 (H7) HA (or the globular head domain of an A/Canada/504/04 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/444/04 (H7) HA (or the globular head domain of an A/Canada/444/04 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/chicken/Jalisco/CPA1/2012 (H7) HA (or the globular head domain of an A/chicken/Jalisco/CPA1/2012 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Alberta/24/2001 (H7) HA (or the globular head domain of an A/mallard/Alberta/24/2001 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/rhea/NC/39482/93 (H7) HA (or the globular head domain of an A/rhea/NC/39482/93 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA) and

the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Netherlands/12/2000 (H7) HA (or the globular head domain of an A/mallard/Netherlands/12/2000 (H7)-like influenza virus HA).

**[0032]** In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Netherlands/219/03 (H7) HA (or the globular head domain of an A/Netherlands/219/03 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/504/04 (H7) HA (or the globular head domain of an A/Canada/504/04 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/444/04 (H7) HA (or the globular head domain of an A/Canada/444/04 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/chicken/Jalisco/CPA1/2012 (H7) HA (or the globular head domain of an A/chicken/Jalisco/CPA1/2012 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Alberta/24/2001 (H7) HA (or the globular head domain of an A/mallard/Alberta/24/2001 (H7)-like influenza virus HA). In

another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/rhea/NC/39482/93 (H7) HA (or the globular head domain of an A/rhea/NC/39482/93 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Netherlands/12/2000 (H7) HA (or the globular head domain of an A/mallard/Netherlands/12/2000 (H7)-like influenza virus HA).

**[0033]** In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Netherlands/219/03 (H7) HA (or the globular head domain of an A/Netherlands/219/03 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/504/04 (H7) HA (or the globular head domain of an A/Canada/504/04 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/444/04 (H7) HA (or the globular head domain of an A/Canada/444/04 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA)

and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/chicken/Jalisco/CPA1/2012 (H7) HA (or the globular head domain of an A/chicken/Jalisco/CPA1/2012 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Alberta/24/2001 (H7) HA (or the globular head domain of an A/mallard/Alberta/24/2001 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/rhea/NC/39482/93 (H7) HA (or the globular head domain of an A/rhea/NC/39482/93 (H7)-like influenza virus HA). In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA) and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Netherlands/12/2000 (H7) HA (or the globular head domain of an A/mallard/Netherlands/12/2000 (H7)-like influenza virus HA).

**[0034]** In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide provided herein comprises (i) the stem domain of the hemagglutinin from an influenza B virus and (ii) the globular head domain of the hemagglutinin from a different influenza B virus strain (sometimes referred to herein as a "cB/B chimeric influenza hemagglutinin polypeptide").

**[0035]** In a specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA). In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA) and the globular head domain of the cB/B chimeric influenza hemagglutinin polypeptide is the globular head domain of B/Lee/1940 HA (or the globular head domain of an B/Lee/1940-like influenza virus HA). In another specific embodiment, the stem domain of a cB/B chimeric

influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA (or the stem domain of an B/Malaysia/2506/2004-like influenza virus HA) and the globular head domain of the cB/B chimeric influenza hemagglutinin polypeptide is the globular head domain of B/seal/Netherlands/1/99 HA (or the globular head domain of a B/seal/Netherlands/1/99-like influenza virus).

**[0036]** In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA). In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA) and the globular head domain of the cB/B chimeric influenza hemagglutinin polypeptide is the globular head domain of B/Lee/1940 HA (or the globular head domain of a B/Lee/1940-like influenza virus). In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA (or the stem domain of an B/Florida/4/2006-like influenza virus HA) and the globular head domain of the cB/B chimeric influenza hemagglutinin polypeptide is the globular head domain of B/seal/Netherlands/1/99 HA (or the globular head domain of a B/seal/Netherlands/1/99-like influenza virus).

**[0037]** In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA). In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA) and the globular head domain of the cB/B chimeric influenza hemagglutinin polypeptide is the globular head domain of B/Lee/1940 HA (or the globular head domain of a B/Lee/1940-like influenza virus). In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA (or the stem domain of an B/Wisconsin/1/2010-like influenza virus HA) and the globular head domain of the cB/B chimeric influenza hemagglutinin polypeptide is the globular head domain of B/seal/Netherlands/1/99 HA (or the globular head domain of a B/seal/Netherlands/1/99-like influenza virus).

**[0038]** In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA). In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA) and the globular head domain of the cB/B chimeric influenza hemagglutinin polypeptide is the globular head domain of B/Lee/1940 HA (or the globular head domain of a B/Lee/1940-like influenza virus). In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA (or the stem domain of an B/Brisbane/60/2008-like influenza virus HA) and the globular head domain of the cB/B chimeric influenza hemagglutinin polypeptide is the globular head domain of B/seal/Netherlands/1/99 HA (or the globular head domain of a B/seal/Netherlands/1/99-like influenza virus).

**[0039]** In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide provided herein comprises (i) the stem domain of the hemagglutinin from an influenza virus of the H3 subtype and (ii) the globular head domain of the hemagglutinin from an influenza virus of the H4 subtype (sometimes referred to herein as a "cH4/3 chimeric influenza hemagglutinin polypeptide"). In a specific embodiment, the stem domain of a cH4/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/09 HA (or the stem domain of an A/Perth/16/09-like influenza virus HA). In another specific embodiment, the stem domain of a cH4/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/09 HA (or the stem domain of an A/Perth/16/09-like influenza virus HA) and the globular head domain of the cH4/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/duck/Czech/56 (or the globular head domain of an A/duck/Czech/56-like influenza virus HA).

**[0040]** In specific embodiments, the chimeric influenza hemagglutinin polypeptides described herein are soluble, e.g., are soluble in compositions, e.g., the compositions described herein. Exemplary methods for generating soluble chimeric influenza hemagglutinin polypeptides are described in Section 6.6.1.2, infra.

**[0041]** When designing the foregoing chimeric influenza HA polypeptides, care should be taken to maintain the stability of the resulting protein. In this regard, in certain embodiments, it is recommended that for chimeric influenza hemagglutinin polypeptides comprising stem

domains from influenza A viruses, the cysteine residues identified as Ap and Aq in Fig. 1 be maintained since they contribute to the stability of the HA stalk as discussed in more detail in Section 5.1 infra. For example, for the best stability, it is preferred to "swap" the HA globular domain as a whole (between the Ap and Aq cysteine residues as shown in Fig. 1) since the resulting conformation would be closest to the native structure. Similarly, chimeric influenza hemagglutinin polypeptides comprising the stem domains of influenza B viruses may utilize cysteines present in the globular head domains of the influenza A virus from which the globular head domain of the chimeric influenza hemagglutinin polypeptide is obtained (see, e.g., Figure 36).

**[0042]** In another aspect, provided herein are immunogenic compositions (e.g., vaccine formulations) comprising one, two, or more of the chimeric influenza hemagglutinin polypeptides described herein. In certain embodiments, the immunogenic compositions (e.g., vaccine formulations) provided herein may comprise chimeric influenza hemagglutinin polypeptide(s) described herein, influenza viruses (e.g., live or killed virus) that comprise a chimeric influenza hemagglutinin polypeptide(s) described herein or a genome engineered to encode chimeric influenza hemagglutinin polypeptide(s) described herein; or vectors or cells that comprise a chimeric influenza hemagglutinin polypeptide(s) described herein or a genome engineered to encode chimeric influenza hemagglutinin polypeptide(s) described herein. In certain embodiments, the immunogenic compositions provided herein may comprise (i) a cH5/1 chimeric influenza hemagglutinin polypeptide described herein, a cH5/3 chimeric influenza hemagglutinin polypeptide described herein, a cH7/3 chimeric influenza hemagglutinin polypeptide described herein, a cH5/B chimeric influenza hemagglutinin polypeptide described herein, a cH7/B chimeric influenza hemagglutinin polypeptide described herein, or a cHB/B chimeric influenza hemagglutinin polypeptide described herein; (ii) a combination of a cH5/1 chimeric influenza hemagglutinin polypeptide described herein and a cH5/3 chimeric influenza hemagglutinin polypeptide described herein; or a combination of a cH5/1 chimeric influenza hemagglutinin polypeptide described herein and a cH7/3 chimeric influenza hemagglutinin polypeptide described herein; (iii) a combination of a cH5/1 chimeric influenza hemagglutinin polypeptide described herein and a cH5/3 chimeric influenza hemagglutinin polypeptide described herein and either of a cH5/B, a cH7/B, or a cB/B chimeric influenza hemagglutinin polypeptide described herein; or (iv) a combination of a cH5/1 chimeric influenza hemagglutinin

polypeptide described herein and a cH7/3 chimeric influenza hemagglutinin polypeptide described herein and either of a cH5/B, a cH7/B, or a cB/B chimeric influenza hemagglutinin polypeptide described herein.

**[0043]** In a specific embodiment, provided herein are vaccine formulations comprising one or more of the chimeric influenza hemagglutinin polypeptides described herein. In a specific embodiment, provided herein is a monovalent vaccine comprising one of the chimeric influenza hemagglutinin polypeptides described herein. In another specific embodiment, provided herein is a bivalent vaccine comprising two of the chimeric influenza hemagglutinin polypeptides described herein (i.e., two distinct chimeric influenza hemagglutinin polypeptides). In another specific embodiment, provided herein is a trivalent vaccine comprising three of the chimeric influenza hemagglutinin polypeptides described herein (i.e., three distinct chimeric influenza hemagglutinin polypeptides).

**[0044]** The vaccine formulations provided herein may comprise the chimeric influenza hemagglutinin polypeptides described herein in any form. For example, the vaccine formulations provided herein may comprise subunit vaccines comprising one or more of the chimeric influenza hemagglutinin polypeptides described herein (e.g., compositions comprising chimeric influenza hemagglutinin polypeptides, e.g., soluble chimeric influenza hemagglutinin polypeptides); live influenza viruses (e.g., live attenuated influenza viruses) that express one or more of the chimeric influenza hemagglutinin polypeptides described herein; live influenza viruses (e.g., live attenuated influenza viruses) comprising a genome that encodes one or more of the chimeric influenza hemagglutinin polypeptides described herein; killed influenza viruses that comprise one or more of the chimeric influenza hemagglutinin polypeptides described herein; killed influenza viruses comprising a genome that encodes one or more of the chimeric influenza hemagglutinin polypeptides described herein; virus/viral-like particles ("VLPs") that contain one or more of the chimeric influenza hemagglutinin polypeptides described herein; split virus vaccines, wherein said virus expresses one or more of the chimeric influenza hemagglutinin polypeptides described herein and/or comprises a genome that encodes one or more of the chimeric influenza hemagglutinin polypeptides described herein; viral expression vectors (e.g., non-influenza virus expression vectors) that express one or more of the chimeric influenza hemagglutinin polypeptides described herein; and bacterial expression vectors that express one or more of the chimeric influenza hemagglutinin polypeptides described herein.

**[0045]** The vaccine formulations described herein can elicit highly potent and broadly neutralizing antibodies against the HA stem domain of the chimeric influenza hemagglutinin polypeptides. Such "universal" vaccines can be used to induce and/or boost cross-protective immune responses across influenza virus subtypes.

**[0046]** In another aspect, provided herein are methods of immunizing a subject against an influenza virus disease or infection comprising administering to the subject a composition comprising one or more of the chimeric influenza hemagglutinin (HA) polypeptides described herein or a vaccine formulation described herein. In certain embodiments, a subject is primed with a first composition comprising one or more of the chimeric influenza hemagglutinin (HA) polypeptides described herein or a vaccine formulation described herein, and later boosted with the same or a different composition (e.g., a composition comprising a different chimeric influenza hemagglutinin (HA) polypeptide; a composition comprising the same chimeric influenza hemagglutinin (HA) polypeptide but in a different context (e.g., the first composition comprises a subunit vaccine comprising a chimeric influenza hemagglutinin (HA) polypeptide and the different composition comprises a viral vector that comprises the same chimeric influenza hemagglutinin (HA) polypeptide), or a composition comprising a different chimeric influenza hemagglutinin (HA) polypeptide in a different context) comprising one or more of the chimeric influenza hemagglutinin (HA) polypeptides described herein or a vaccine formulation described herein. The subject may be boosted once, or more than once with a composition comprising one or more of the chimeric influenza hemagglutinin (HA) polypeptides described herein or a vaccine formulation described herein. In certain embodiments, when the subject is boosted more than once, the first and the second boosts are with different compositions comprising one or more of the chimeric influenza hemagglutinin (HA) polypeptides described herein or a vaccine formulation described herein, and each boost comprises a different composition than the composition comprising one or more of the chimeric influenza hemagglutinin (HA) polypeptides described herein or a vaccine formulation described herein used to prime the subject.

**[0047]** In a specific embodiment, provided herein is a method of immunizing a subject (e.g., a human subject) against influenza virus comprising administering to the subject a first dose of an effective amount of a chimeric influenza hemagglutinin (HA) polypeptide described herein, a vector described herein, an immunogenic composition described herein, or a vaccine formulation

described herein and administering to the subject a second dose of an effective amount of a chimeric influenza hemagglutinin (HA) polypeptide described herein, a vector described herein, an immunogenic composition described herein, or a vaccine formulation described herein 30 days to 6 months after the subject has received the first dose, wherein (i) the chimeric influenza hemagglutinin (HA) polypeptide or the chimeric influenza hemagglutinin (HA) polypeptide of the vector, the immunogenic composition, or vaccine formulation in the first and second doses are the same or different (e.g., the globular head of the chimeric influenza hemagglutinin (HA) polypeptide administered in the first dose is different than the the globular head of the chimeric influenza hemagglutinin (HA) polypeptide administered in the second dose); and/or (ii) the type of immunogenic composition or vector or vaccine formulation administered in both doses are the same or different. In certain embodiments, the method comprises administering to the subject a third dose of an effective amount of a chimeric influenza hemagglutinin (HA) polypeptide described herein, a vector described herein, an immunogenic composition described herein, or a vaccine formulation described herein 30 days to 6 months after the subject has received the second dose, wherein (i) the chimeric influenza hemagglutinin (HA) polypeptide or the chimeric influenza hemagglutinin (HA) polypeptide of the vector, the immunogenic composition, or vaccine formulation is the same or different than the chimeric influenza hemagglutinin (HA) polypeptide in the first and/or second dose; and (ii) the type of immunogenic composition or vector or vaccine formulation administered in both doses are the same or different. In certain embodiments, two, three, or more chimeric influenza hemagglutinin (HA) polypeptides are administered as part of the first, second, and/or third doses, wherein each chimeric HA polypeptide in a dose is different from each other. In some embodiments, the first, second, and/or third dose of the vector, the immunogenic composition, or vaccine formulation comprises two, three, or more chimeric influenza hemagglutinin (HA) polypeptides, wherein each chimeric influenza hemagglutinin (HA) polypeptide in the vector, the immunogenic composition, or vaccine formulation administered in a dose is different from each other (e.g., the globular head of the chimeric influenza hemagglutinin (HA) polypeptide administered in the first dose is different than the the globular head of the chimeric influenza hemagglutinin (HA) polypeptide administered in the second dose, etc.).

**[0048]** In another specific embodiment, provided herein is a method of immunizing a 1-5 year old human subject against influenza virus comprising administering to the subject a first

dose of an effective amount of a chimeric influenza hemagglutinin (HA) polypeptide described herein, a vector described herein, an immunogenic composition described herein, or a vaccine formulation described herein and administering to the subject a second dose of an effective amount of a chimeric influenza hemagglutinin (HA) polypeptide described herein, a vector described herein, an immunogenic composition described herein, or a vaccine formulation described herein 30 days to 6 months after the subject has received the first dose, wherein (i) the chimeric influenza hemagglutinin (HA) polypeptide or the chimeric influenza hemagglutinin (HA) polypeptide of the vector, the immunogenic composition, or vaccine formulation in the first and second doses are the same or different (e.g., the globular head of the chimeric influenza hemagglutinin (HA) polypeptide administered in the first dose is different than the the globular head of the chimeric influenza hemagglutinin (HA) polypeptide administered in the second dose); and/or (ii) the type of immunogenic composition or vector or vaccine formulation administered in both doses are the same or different. In certain embodiments, the method comprises administering to the subject a third dose of an effective amount of a chimeric influenza hemagglutinin (HA) polypeptide described herein, a vector described herein, an immunogenic composition described herein, or a vaccine formulation described herein 30 days to 6 months after the subject has received the second dose, wherein (i) the chimeric influenza hemagglutinin (HA) polypeptide or the chimeric influenza hemagglutinin (HA) polypeptide of the vector, the immunogenic composition, or vaccine formulation in the first and second doses are the same or different (e.g., the globular head of the chimeric influenza hemagglutinin (HA) polypeptide administered in the first dose is different than the the globular head of the chimeric influenza hemagglutinin (HA) polypeptide administered in the second dose); and/or (ii) the type of immunogenic composition or vector or vaccine formulation administered in both doses are the same or different. In certain embodiments, two, three, or more chimeric influenza hemagglutinin (HA) polypeptides are administered as part of the first, second, and/or third doses, wherein each chimeric HA polypeptide in a dose is different from each other. In some embodiments, the first, second, and/or third dose of the vector, the immunogenic composition, or vaccine formulation comprises two, three, or more chimeric influenza hemagglutinin (HA) polypeptides, wherein each chimeric influenza hemagglutinin (HA) polypeptide in the vector, the immunogenic composition, or vaccine formulation administered in a dose is different from each other (e.g., the globular head of the chimeric influenza hemagglutinin (HA) polypeptide administered in the first

dose is different than the the globular head of the chimeric influenza hemagglutinin (HA) polypeptide administered in the second dose, etc.).

**[0049]** In another aspect, provided herein are kits comprising one or more of the chimeric influenza hemagglutinin (HA) polypeptides described herein or a vaccine formulation described herein. The kits provided herein may further comprise one or more additional components, e.g., an antibody that specifically binds one or more of the chimeric influenza hemagglutinin (HA) polypeptides provided in the kit.

**[0050]** The working Examples (e.g., Section 6, Examples) demonstrate, *inter alia*, the production of constructs encoding chimeric influenza HA polypeptides comprising an HA stem domain and displaying a heterologous HA globular head domain, and the production of stable chimeric HA polypeptides from these constructs which are cross-reactive with antibodies to both the stem domain and the head domain. The working Examples also illustrate the use of such constructs in the generation of a protective immune response in subjects against multiple different strains and subtypes of influenza virus, i.e., the Examples demonstrate that the chimeric influenza HA polypeptides described herein can be used as a universal influenza vaccine.

## 3.1 TERMINOLOGY

**[0051]** The terms "about" or "approximate," when used in reference to an amino acid position refer to the particular amino acid position in a sequence or any amino acid that is within five, four, three, two, or one residues of that amino acid position, either in an N-terminal direction or a C-terminal direction.

**[0052]** As used herein, the term "about" or "approximately" when used in conjunction with a number refers to any number within 1, 5 or 10% of the referenced number. In certain embodiments, the term "about" encompasses the exact number recited.

**[0053]** As used herein, the term "fragment" in the context of a nucleic acid sequence refers to a nucleotide sequence comprising a portion of consecutive nucleotides from a parent sequence. In a specific embodiment, the term refers to a nucleotide sequence of 5 to 15, 5 to 25, 10 to 30, 15 to 30, 10 to 60, 25 to 100, 150 to 300 or more consecutive nucleotides from a parent sequence. In another embodiment, the term refers to a nucleotide sequence of at least 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 110, 125, 150, 175, 200, 250, 275, 300, 325, 350, 375, 400, 425, 450 or 475 consecutive nucleotides of a parent sequence.

**[0054]** As used herein, the term "fragment" in the context of an amino acid sequence refers to an amino acid sequence comprising a portion of consecutive amino acid residues from a parent sequence. In a specific embodiment, the term refers to an amino acid sequence of 2 to 30, 5 to 30, 10 to 60, 25 to 100, 150 to 300 or more consecutive amino acid residues from a parent sequence. In another embodiment, the term refers to an amino acid sequence of at least 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 110, 125, 150, 175, or 200 consecutive amino acid residues of a parent sequence.

**[0055]** As used herein, the terms "disease" and "disorder" are used interchangeably to refer to a condition in a subject. In specific embodiments, a term "disease" refers to the pathological state resulting from the presence of the virus in a cell or a subject, or by the invasion of a cell or subject by the virus. In certain embodiments, the condition is a disease in a subject, the severity of which is decreased by inducing an immune response in the subject through the administration of an immunogenic composition.

**[0056]** As used herein, the term "effective amount" in the context of administering a therapy to a subject refers to the amount of a therapy which has a prophylactic and/or therapeutic effect(s). In certain embodiments, an "effective amount" in the context of administration of a therapy to a subject refers to the amount of a therapy which is sufficient to achieve one, two, three, four, or more of the following effects: (i) reduce or ameliorate the severity of an influenza virus infection, disease or symptom associated therewith; (ii) reduce the duration of an influenza virus infection, disease or symptom associated therewith; (iii) prevent the progression of an influenza virus infection, disease or symptom associated therewith; (iv) cause regression of an influenza virus infection, disease or symptom associated therewith; (v) prevent the development or onset of an influenza virus infection, disease or symptom associated therewith; (vi) prevent the recurrence of an influenza virus infection, disease or symptom associated therewith; (vii) reduce or prevent the spread of an influenza virus from one cell to another cell, one tissue to another tissue, or one organ to another organ; (ix) prevent or reduce the spread of an influenza virus from one subject to another subject; (x) reduce organ failure associated with an influenza virus infection; (xi) reduce hospitalization of a subject; (xii) reduce hospitalization length; (xiii) increase the survival of a subject with an influenza virus infection or disease associated therewith; (xiv) eliminate an influenza virus infection or disease associated therewith; (xv) inhibit or reduce influenza virus replication; (xvi) inhibit or reduce the entry of an influenza virus

into a host cell(s); (xviii) inhibit or reduce replication of the influenza virus genome; (xix) inhibit or reduce synthesis of influenza virus proteins; (xx) inhibit or reduce assembly of influenza virus particles; (xxi) inhibit or reduce release of influenza virus particles from a host cell(s); (xxii) reduce influenza virus titer; and/or (xxiii) enhance or improve the prophylactic or therapeutic effect(s) of another therapy.

**[0057]** In certain embodiments, the effective amount does not result in complete protection from an influenza virus disease, but results in a lower titer or reduced number of influenza viruses compared to an untreated subject. In certain embodiments, the effective amount results in a 0.5 fold, 1 fold, 2 fold, 4 fold, 6 fold, 8 fold, 10 fold, 15 fold, 20 fold, 25 fold, 50 fold, 75 fold, 100 fold, 125 fold, 150 fold, 175 fold, 200 fold, 300 fold, 400 fold, 500 fold, 750 fold, or 1,000 fold or greater reduction in titer of influenza virus relative to an untreated subject. In some embodiments, the effective amount results in a reduction in titer of influenza virus relative to an untreated subject of approximately 1 log or more, approximately 2 logs or more, approximately 3 logs or more, approximately 4 logs or more, approximately 5 logs or more, approximately 6 logs or more, approximately 7 logs or more, approximately 8 logs or more, approximately 9 logs or more, approximately 10 logs or more, 1 to 3 logs, 1 to 5 logs, 1 to 8 logs, 1 to 9 logs, 2 to 10 logs, 2 to 5 logs, 2 to 7 logs, 2 logs to 8 logs, 2 to 9 logs, 2 to 10 logs 3 to 5 logs, 3 to 7 logs, 3 to 8 logs, 3 to 9 logs, 4 to 6 logs, 4 to 8 logs, 4 to 9 logs, 5 to 6 logs, 5 to 7 logs, 5 to 8 logs, 5 to 9 logs, 6 to 7 logs, 6 to 8 logs, 6 to 9 logs, 7 to 8 logs, 7 to 9 logs, or 8 to 9 logs. Benefits of a reduction in the titer, number or total burden of influenza virus include, but are not limited to, less severe symptoms of the infection, fewer symptoms of the infection and a reduction in the length of the disease associated with the infection.

**[0058]** "Hemagglutinin" and "HA" refer to any hemagglutinin known to those of skill in the art. In certain embodiments, the hemagglutinin is influenza hemagglutinin, such as an influenza A hemagglutinin, an influenza B hemagglutinin, or an influenza C hemagglutinin. A typical hemagglutinin comprises domains known to those of skill in the art including a signal peptide (optional herein), a stem domain, a globular head domain, a luminal domain (optional herein), a transmembrane domain (optional herein) and a cytoplasmic domain (optional herein). In certain embodiments, a hemagglutinin consists of a single polypeptide chain, such as HA0. In certain embodiments, a hemagglutinin consists of more than one polypeptide chain in quaternary association, *e.g.* HA1 and HA2. Those of skill in the art will recognize that an immature HA0

might be cleaved to release a signal peptide (approximately 20 amino acids) yielding a mature hemagglutinin HA0. A hemagglutinin HA0 might be cleaved at another site to yield HA1 polypeptide (approximately 320 amino acids, including the globular head domain and a portion of the stem domain) and HA2 polypeptide (approximately 220 amino acids, including the remainder of the stem domain, a luminal domain, a transmembrane domain and a cytoplasmic domain). In certain embodiments, a hemagglutinin comprises a signal peptide, a transmembrane domain and a cytoplasmic domain. In certain embodiments, a hemagglutinin lacks a signal peptide, *i.e.* the hemagglutinin is a mature hemagglutinin. In certain embodiments, a hemagglutinin lacks a transmembrane domain or cytoplasmic domain, or both. As used herein, the terms "hemagglutinin" and "HA" encompass hemagglutinin polypeptides that are modified by post-translational processing such as signal peptide cleavage, disulfide bond formation, glycosylation (*e.g.*, *N*-linked glycosylation), protease cleavage and lipid modification (*e.g.* S-palmitoylation).

**[0059]** As used herein, the terms "chimeric influenza virus hemagglutinin polypeptide," "chimeric influenza virus HA polypeptide," "chimeric hemagglutinin polypeptide" and "chimeric influenza hemagglutinin polypeptide" refer to an influenza hemagglutinin that comprises an influenza virus hemagglutinin stem domain and an influenza virus hemagglutinin globular head domain, wherein the influenza virus hemagglutinin head domain is heterologous to the influenza virus hemagglutinin stem domain (i.e., the globular head domain of the chimeric influenza virus hemagglutinin polypeptide is from a different strain or subtype of influenza virus than the stem domain of the chimeric influenza virus hemagglutinin polypeptide).

**[0060]** "HA1 N-terminal stem segment" refers to a polypeptide segment that corresponds to the amino-terminal portion of the stem domain of an influenza hemagglutinin HA1 polypeptide. In certain embodiments, an HA1 N-terminal stem segment consists of amino acid residues corresponding approximately to amino acids $HA1_{N\text{-}term}$ through $A_p$ of an HA1 domain. $HA1_{N\text{-}term}$ is the N-terminal amino acid of HA1 as recognized by those of skill in the art. $A_p$ is the cysteine residue in the HA1 N-terminal stem segment that forms or is capable of forming a disulfide bond with a cysteine residue in an HA1 C-terminal stem segment. Residue $A_p$ is identified in influenza A hemagglutinin polypeptides in FIG. 1. Exemplary HA1 N-terminal stem segments are described herein. In certain embodiments, an HA1 N-terminal stem segment consists of amino acid residues corresponding approximately to amino acids 1-52 of HA1 from an H3

hemagglutinin. Note that, in this numbering system, 1 refers to the N-terminal amino acid of the mature HA0 protein, from which the signal peptide has been removed. Those of skill in the art will readily be able recognize the amino acid residues that correspond to the HA1 N-terminal stem segment of other influenza HA polypeptides, e.g., the amino acid residues that correspond to the HA1 N-terminal stem segment of HA1 from an H1 hemagglutinin (see, e.g., Figure 1).

**[0061]** "HA1 C-terminal stem segment" refers to a polypeptide segment that corresponds to the carboxy-terminal portion of the stem domain of an influenza hemagglutinin HA1 polypeptide. In certain embodiments, an HA1 C-terminal stem segment consists of amino acid residues corresponding approximately to amino acids $A_q$ through $HA1_{C\text{-}term}$ of an HA1 domain. $HA1_{C\text{-}term}$ is the C-terminal amino acid of the HA1 domain as recognized by those of skill in the art. Residue $A_q$ is identified in influenza A hemagglutinin polypeptides in FIG. 1. Exemplary HA1 C-terminal stem segments are described herein. In certain embodiments, an HA1 C-terminal stem segment consists of amino acid residues corresponding approximately to amino acids 277-346 of HA1 from an H3 hemagglutinin. Note that, in this numbering system, 1 refers to the N-terminal amino acid of the mature HA0 protein, from which the signal peptide has been removed. Those of skill in the art will readily be able recognize the amino acid residues that correspond to the HA1 C-terminal stem segment of other influenza HA polypeptides, e.g., the amino acid residues that correspond to the HA1 C-terminal stem segment of HA1 from an H1 hemagglutinin (see, e.g., Figure 1).

**[0062]** "HA2" refers to a polypeptide domain that corresponds to the HA2 domain of an influenza hemagglutinin polypeptide known to those of skill in the art. In certain embodiments, an HA2 consists of a stem domain, a luminal domain, a transmembrane domain and a cytoplasmic domain (*see, e.g.,* Scheiffle *et al.,* 2007, *EMBO J.* 16(18):5501-5508, the contents of which are incorporated by reference in their entirety). In certain embodiments, an HA2 consists of a stem domain, a luminal domain and a transmembrane domain. In certain embodiments, an HA2 consists of a stem domain and a luminal domain; in such embodiments, the HA2 might be soluble. In certain embodiments, an HA2 consists of a stem domain; in such embodiments, the HA2 might be soluble.

**[0063]** As used herein, the term "heterologous" in the context of a polypeptide, nucleic acid or virus refers to a polypeptide, nucleic acid or virus, respectively, that is not normally found in nature or not normally associated in nature with a polypeptide, nucleic acid or virus of interest.

For example, a "heterologous polypeptide" may refer to a polypeptide derived from a different virus, *e.g.*, a different influenza strain or subtype, or an unrelated virus or different species. In specific embodiments, when used in the context of a globular head domain of a chimeric influenza virus hemagglutinin described herein, the term heterologous refers to an influenza HA globular head domain that is associated with an influenza HA stem domain that it would not normally be found associated with (e.g., the head and stem domains of the HA would not be found together in nature).

**[0064]** As used herein, the term "in combination," in the context of the administration of two or more therapies to a subject, refers to the use of more than one therapy (*e.g.*, more than one prophylactic agent and/or therapeutic agent). The use of the term "in combination" does not restrict the order in which therapies are administered to a subject. For example, a first therapy (*e.g.*, a first prophylactic or therapeutic agent) can be administered prior to (*e.g.*, 5 minutes, 15 minutes, 30 minutes, 45 minutes, 1 hour, 2 hours, 4 hours, 6 hours, 12 hours, 16 hours, 24 hours, 48 hours, 72 hours, 96 hours, 1 week, 2 weeks, 3 weeks, 4 weeks, 5 weeks, 6 weeks, 8 weeks, or 12 weeks before), concomitantly with, or subsequent to (*e.g.*, 5 minutes, 15 minutes, 30 minutes, 45 minutes, 1 hour, 2 hours, 4 hours, 6 hours, 12 hours, 16 hours, 24 hours, 48 hours, 72 hours, 96 hours, 1 week, 2 weeks, 3 weeks, 4 weeks, 5 weeks, 6 weeks, 8 weeks, or 12 weeks after) the administration of a second therapy to a subject.

**[0065]** As used herein, the term "infection" means the invasion by, multiplication and/or presence of a virus in a cell or a subject. In one embodiment, an infection is an "active" infection, *i.e.*, one in which the virus is replicating in a cell or a subject. Such an infection is characterized by the spread of the virus to other cells, tissues, and/or organs, from the cells, tissues, and/or organs initially infected by the virus. An infection may also be a latent infection, *i.e.*, one in which the virus is not replicating.

**[0066]** As used herein, the term "influenza virus disease" refers to the pathological state resulting from the presence of an influenza virus (*e.g.*, influenza A or B virus) in a cell or subject or the invasion of a cell or subject by an influenza virus. In specific embodiments, the term refers to a respiratory illness caused by an influenza virus.

**[0067]** As used herein, the phrases "IFN deficient system" or "IFN-deficient substrate" refer to systems, *e.g.*, cells, cell lines and animals, such as pigs, mice, chickens, turkeys, rabbits, rats, etc., which do not produce IFN or produce low levels of IFN (*i.e.*, a reduction in IFN expression

of 5-10%, 10-20%, 20-30%, 30-40%, 40-50%, 50-60%, 60-70%, 70-80%, 80-90% or more when compared to IFN-competent systems under the same conditions), do not respond or respond less efficiently to IFN, and/or are deficient in the activity of one or more antiviral genes induced by IFN.

**[0068]** As used herein, the term "like," when used in the context of an "influenza-like virus," refers an influenza virus that represents a different isolate of the referenced influenza virus, wherein the amino acid sequence of said different isolate, or of the amino acid sequence of the HA of said different isolate, is identical to, or nearly identical to, the amino acid sequence of the referenced influenza virus or the amino acid sequence of the HA of the referenced influenza virus; and/or the immune response against said different isolate confers full protection against the referenced influenza virus, and vice versa. In certain embodiments, an influenza virus isolate that has an amino acid sequence that is nearly identical to the amino acid sequence of a referenced influenza virus has an amino acid sequence that is at least 90%, 91%, 92%, 93%, 94%, 95%, 96%, 97%, 98%, 99%, or 99.5% identical to the amino acid sequence of the referenced influenza virus. In certain embodiments, an influenza virus isolate that represents an "influenza-like virus" comprises an HA that has an amino acid sequence that is nearly identical to the amino acid sequence of the HA of a referenced influenza virus, e.g., the HA of the influenza-like virus has an amino acid sequence that is at least 90%, 91%, 92%, 93%, 94%, 95%, 96%, 97%, 98%, 99%, or 99.5% identical to the amino acid sequence of the HA of the referenced influenza virus.

**[0069]** As used herein, the numeric term "log" refers to $\log_{10}$.

**[0070]** As used herein, the phrase "majority of the population is naive to," in reference to a strain or subtype (e.g., an H1 subtype) of influenza virus, refers to a strain or subtype of influenza virus that greater than 50% of the human population has presumably not been exposed to. In specific embodiments, the phrase "majority of the population is naive to," refers to a strain or subtype of influenza virus that at least 60%, 70%, 75%, 80%, 85%, 90%, 95%, or 99% f the human population has presumably not been exposed to.

**[0071]** As used herein, the phrase "multiplicity of infection" or "MOI" is the average number of infectious virus particles per infected cell. The MOI is determined by dividing the number of infectious virus particles added (ml added x PFU/ml) by the number of cells added (ml added x cells/ml).

**[0072]** As used herein, the term "nucleic acid" is intended to include DNA molecules (*e.g.*, cDNA or genomic DNA) and RNA molecules (*e.g.*, mRNA) and analogs of the DNA or RNA generated using nucleotide analogs. The nucleic acid can be single-stranded or double-stranded.

**[0073]** As used herein, the term "polypeptide" refers to a polymer of amino acids linked by amide bonds as is known to those of skill in the art. As used herein, the term polypeptide can refer to a single polypeptide chain linked by covalent amide bonds. The term can also refer to multiple polypeptide chains associated by non-covalent interactions such as ionic contacts, hydrogen bonds, Van der Waals contacts and hydrophobic contacts. Those of skill in the art will recognize that the term includes polypeptides that have been modified, for example by post-translational processing such as signal peptide cleavage, disulfide bond formation, glycosylation (*e.g.*, *N*-linked glycosylation), protease cleavage and lipid modification (*e.g.* S-palmitoylation).

**[0074]** As used herein, the terms "prevent," "preventing" and "prevention" in the context of the administration of a therapy(ies) to a subject to prevent an influenza virus disease refer to one or more of the prophylactic/beneficial effects resulting from the administration of a therapy or a combination of therapies. In a specific embodiment, the terms "prevent," "preventing" and "prevention" in the context of the administration of a therapy(ies) to a subject to prevent an influenza virus disease refer to one or more of the following effects resulting from the administration of a therapy or a combination of therapies: (i) the inhibition of the development or onset of an influenza virus disease or a symptom thereof; (ii) the inhibition of the recurrence of an influenza virus disease or a symptom associated therewith; and (iii) the reduction or inhibition in influenza virus infection and/or replication.

**[0075]** As used herein, the terms "purified" and "isolated" when used in the context of a polypeptide (including an antibody) that is obtained from a natural source, *e.g.*, cells, refers to a polypeptide which is substantially free of contaminating materials from the natural source, *e.g.*, soil particles, minerals, chemicals from the environment, and/or cellular materials from the natural source, such as but not limited to cell debris, cell wall materials, membranes, organelles, the bulk of the nucleic acids, carbohydrates, proteins, and/or lipids present in cells. Thus, a polypeptide that is isolated includes preparations of a polypeptide having less than about 30%, 20%, 10%, 5%, 2%, or 1% (by dry weight) of cellular materials and/or contaminating materials. As used herein, the terms "purified" and "isolated" when used in the context of a polypeptide (including an antibody) that is chemically synthesized refers to a polypeptide which is

substantially free of chemical precursors or other chemicals which are involved in the syntheses of the polypeptide. In a specific embodiment, a chimeric influenza hemagglutinin (HA) polypeptide is chemically synthesized. In another specific embodiment, an influenza hemagglutinin stem domain polypeptide, an influenza hemagglutinin head domain polypeptide, and/or a chimeric influenza hemagglutinin polypeptide is isolated.

**[0076]** As used herein, the terms "replication," "viral replication" and "virus replication" in the context of a virus refer to one or more, or all, of the stages of a viral life cycle which result in the propagation of virus. The steps of a viral life cycle include, but are not limited to, virus attachment to the host cell surface, penetration or entry of the host cell (*e.g.*, through receptor mediated endocytosis or membrane fusion), uncoating (the process whereby the viral capsid is removed and degraded by viral enzymes or host enzymes thus releasing the viral genomic nucleic acid), genome replication, synthesis of viral messenger RNA (mRNA), viral protein synthesis, and assembly of viral ribonucleoprotein complexes for genome replication, assembly of virus particles, post-translational modification of the viral proteins, and release from the host cell by lysis or budding and acquisition of a phospholipid envelope which contains embedded viral glycoproteins. In some embodiments, the terms "replication," "viral replication" and "virus replication" refer to the replication of the viral genome. In other embodiments, the terms "replication," "viral replication" and "virus replication" refer to the synthesis of viral proteins.

**[0077]** As used herein, the terms "stem domain polypeptide," "HA stem domain," "influenza virus hemagglutinin stem domain polypeptide" and "HA stalk domain" refer to polypeptide comprising or consisting of one or more polypeptide chains that make up a stem domain of an influenza hemagglutinin. A stem domain polypeptide might be a single polypeptide chain, two polypeptide chains or more polypeptide chains. Typically, a stem domain polypeptide is a single polypeptide chain (i.e. corresponding to the stem domain of a hemagglutinin HA0 polypeptide) or two polypeptide chains (i.e. corresponding to the stem domain of a hemagglutinin HA1 polypeptide in association with a hemagglutinin HA2 polypeptide). In specific embodiments, a stem domain polypeptide is derived from an influenza A H1 or H3 influenza virus hemagglutinin, or an influenza B influenza virus hemagglutinin.

**[0078]** As used herein, the terms "influenza virus hemagglutinin head domain polypeptide," "influenza virus hemagglutinin head domain," "HA globular head domain," and "HA head domain" refer to the globular head domain of an influenza hemagglutinin polypeptide. For

example, for influenza A virus, the globular head domain is generally understood to be present between two key cysteine residues in the HA1 portion of the HA molecule. These cysteine residues are identified as "Ap" and "Aq" in Fig. 1 for various influenza A viruses.

**[0079]** As used herein, the terms "subject" or "patient" are used interchangeably to refer to an animal (*e.g.*, birds, reptiles, and mammals). In a specific embodiment, a subject is a bird. In another embodiment, a subject is a mammal including a non-primate (*e.g.*, a camel, donkey, zebra, cow, pig, horse, goat, sheep, cat, dog, rat, and mouse) and a primate (*e.g.*, a monkey, chimpanzee, and a human). In certain embodiments, a subject is a non-human animal. In some embodiments, a subject is a farm animal or pet. In another embodiment, a subject is a human. In another embodiment, a subject is a human infant. In another embodiment, a subject is a human child. In another embodiment, a subject is a human adult. In another embodiment, a subject is an elderly human. In another embodiment, a subject is a premature human infant.

**[0080]** As used herein, the term "premature human infant" refers to a human infant born at less than 37 weeks of gestational age.

**[0081]** As used herein, the term "human infant" refers to a newborn to 1 year old human.

**[0082]** As used herein, the term "human child" refers to a human that is 1 year to 18 years old.

**[0083]** As used herein, the term "human adult" refers to a human that is 18 years or older.

**[0084]** As used herein, the term "elderly human" refers to a human 65 years or older.

**[0085]** As used herein, the term "seasonal influenza virus strain" refers to a strain of influenza virus to which a subject population is exposed to on a seasonal basis. In specific embodiments, the term seasonal influenza virus strain refers to a strain of influenza A virus. In specific embodiments, the term seasonal influenza virus strain refers to a strain of influenza virus that belongs to the H1 or the H3 subtype, i.e., the two subtypes that presently persist in the human subject population. In other embodiments, the term seasonal influenza virus strain refers to a strain of influenza B virus.

**[0086]** As used herein, the terms "therapies" and "therapy" can refer to any protocol(s), method(s), compound(s), composition(s), formulation(s), and/or agent(s) that can be used in the prevention or treatment of a viral infection or a disease or symptom associated therewith. In certain embodiments, the terms "therapies" and "therapy" refer to biological therapy, supportive therapy, and/or other therapies useful in treatment or prevention of a viral infection or a disease

or symptom associated therewith known to one of skill in the art. In some embodiments, the term "therapy" refers to (i) a nucleic acid encoding a chimeric influenza hemagglutinin (HA) polypeptide, (ii) a chimeric influenza hemagglutinin (HA) polypeptide, or (iii) a vector or composition comprising a nucleic acid encoding a chimeric influenza hemagglutinin (HA) polypeptide or comprising a chimeric influenza hemagglutinin (HA) polypeptide. In some embodiments, the term "therapy" refers to an antibody that specifically binds to a chimeric influenza virus hemagglutinin polypeptide.

**[0087]** As used herein, the terms "treat," "treatment," and "treating" refer in the context of administration of a therapy(ies) to a subject to treat an influenza virus disease or infection to obtain a beneficial or therapeutic effect of a therapy or a combination of therapies. In specific embodiments, such terms refer to one, two, three, four, five or more of the following effects resulting from the administration of a therapy or a combination of therapies: (i) the reduction or amelioration of the severity of an influenza virus infection or a disease or a symptom associated therewith; (ii) the reduction in the duration of an influenza virus infection or a disease or a symptom associated therewith; (iii) the regression of an influenza virus infection or a disease or a symptom associated therewith; (iv) the reduction of the titer of an influenza virus; (v) the reduction in organ failure associated with an influenza virus infection or a disease associated therewith; (vi) the reduction in hospitalization of a subject; (vii) the reduction in hospitalization length; (viii) the increase in the survival of a subject; (ix) the elimination of an influenza virus infection or a disease or symptom associated therewith; (x) the inhibition of the progression of an influenza virus infection or a disease or a symptom associated therewith; (xi) the prevention of the spread of an influenza virus from a cell, tissue, organ or subject to another cell, tissue, organ or subject; (xii) the inhibition or reduction in the entry of an influenza virus into a host cell(s); (xiii) the inhibition or reduction in the replication of an influenza virus genome; (xiv) the inhibition or reduction in the synthesis of influenza virus proteins; (xv) the inhibition or reduction in the release of influenza virus particles from a host cell(s); and/or (xvi) the enhancement or improvement the therapeutic effect of another therapy.

**[0088]** As used herein, in some embodiments, the phrase "wild-type" in the context of a virus refers to the types of a virus that are prevalent, circulating naturally and producing typical outbreaks of disease. In other embodiments, the term "wild-type" in the context of a virus refers to a parental virus.

## 4. BRIEF DESCRIPTION OF THE DRAWINGS

**[0089]** **Fig. 1** presents a sequence alignment by CLUSTALW of representative sequences of 17 subtypes of influenza virus A hemagglutinin (SEQ ID NOS:1-16 and 35 respectively). The residue designated $A_p$ is the cysteine residue in the HA1 N-terminal stem segment that forms or is capable of forming a disulfide bond with the residue designated $A_q$, a cysteine residue in an HA1 C-terminal stem segment. The residue designated $B_q$ represents the approximate N-terminal amino acid of the HA1 C-terminal short stem segments described herein. The residue designated $C_q$ represents the approximate N-terminal amino acid of the HA1 C-terminal long stem segments described herein. The residue designated $C_p$ represents the approximate C-terminal amino acid of the HA1 N-terminal long stem segments described herein.

**[0090]** **Fig. 2** provides a schematic of chimeric HAs with a conserved H1 stalk domain and different globular head domains from distinct subtype HAs.

**[0091]** **Fig. 3** provides a novel influenza vaccine and diagnostic tool platform to induce and analyze antibodies and reactive sera. A) Expression of chimeric HAs. Chimeric HAs consisting of the stalk domain of A/PR/8/34 HA and the globular head domain of A/California/4/09 (chimeric HA) as well as wild type HAs (PR8-HA and CAL09-HA) and a GFP control were expressed in 293T cells. The upper Western blot was probed with a PR8-specific antibody (PY102) whereas the blot on the lower side was probed with an antibody specific for Cal09 (39C2). B) Schematic drawing of HA constructs expressed in A. The chimeric HA is composed of the A/PR/8/34 HA stalk domain and the 2009 A/California/04/09 globular head domain.

**[0092]** **Fig. 4** provides a schematic of chimeric HAs. A) Basic structure of a chimeric HA. The globular head can be exchanged conveniently at disulfide bond Cys 52-Cys 277. B) Prime-boost regime with sequential administration of chimeric HAs consisting of a completely conserved stalk domain and a varying globular head domain.

**[0093]** **Fig. 5** describes generation of a chimeric HA with the stalk of an H1 HA and the globular head of an H3 HA. A chimeric HA consisting of the stalk domain of A/PR/8/34 HA and the globular head domain of HK/68 (chimeric H3) as well as wild type HAs (PR8-HA and HK68 HA) were expressed in 293T cells. The upper Western blot was probed with a PR8-specific antibody whereas the blot on the lower side was probed with an antibody specific for H3.

**[0094]** **Fig. 6** depicts a sequence comparison of the hemagglutinin protein sequences of A/Hong Kong/1/1968 (H3), A/Perth/16/2009 (H3), A/PR/8/34 (H1), A/Cal/4/09 (H1), A/Viet Nam/1203/04 (H5), and A/mallard/Alberta/24/01 (H7). The Cys52 and Cys277 amino acid residues are specified (based on H3 numbering). The black shade indicates conserved amino acids. The black wavy line represents the globular head region of HAs. The starting points of HA1 and HA2 are indicated. Amino acid sequences from the N-terminus to Cys52 of the HA of each of A/Hong Kong/1/1968 (H3), A/Perth/16/2009 (H3), A/PR/8/34 (H1), A/Cal/4/09 (H1), A/Viet Nam/1203/04 (H5), and A/mallard/Alberta/24/01 (H7) are presented, and correspond to SEQ ID NOs. 23-28, respectively. Amino acid sequences from Cys277 of the HA of each of A/Hong Kong/1/1968 (H3), A/Perth/16/2009 (H3), A/PR/8/34 (H1), A/Cal/4/09 (H1), A/Viet Nam/1203/04 (H5), and A/mallard/Alberta/24/01 (H7) to the C-terminus are presented, and correspond to SEQ ID NOs. 29-34, respectively.

**[0095]** **Fig. 7** depicts a schematic of chimeric hemagglutinins. (A) Construction diagram of the chimeric PR8-cH1 HA. The chimeric HA was constructed by swapping the globular head domain located between Cys52 and Cys277 of A/PR/8/34(H1) HA with that of the A/California/4/09(H1) HA. The resulting chimeric HA has the stalk region of A/PR/8/34 (H1) HA with a globular head domain of the A/California/4/09 (H1) HA designated as PR8-cH1. (B) Schematic of the folded structures of the different wild type and chimeric HAs, such as wild the type PR8 HA, the chimeric PR8-cH1 HA, the chimeric PR8-cH5 HA, the wild type Perth HA, and the chimeric Perth-cH7 HA (from left to right). The full-length HA structures were downloaded from the Protein Database (PDB): PR8 HA (PDB ID 1RU7) and Perth HA (represented by HK68 HA, PDB ID 1MQN). Final images were generated with PyMol (Delano Scientific).

**[0096]** **Fig. 8** depicts the surface expression and functional analysis of chimeric HA constructs. (A) Surface expression of chimeric HA constructs was evaluated in transiently transfected cells. At 24 h post-transfection, 293T cells were trypsinized and cell surface expression of chimeric HA proteins were analyzed by flow cytometry. In the upper panels, mock-transfected cells (left shaded region) are compared to cells transfected with PR8 HA (right) or cells transfected with PR8-cH1 (right) or PR8-cH5 (right). In the bottom panels, mock-transfected cells (left shaded region) are compared to cells transfected with Perth and Perth-cH7 constructs (right). (B) Luciferase-encoding pseudo-particles expressing chimeric HAs

were used to infect MDCK cells. The relative light units (RLU) generated in the luciferase assay indicate that pseudo-particles expressing chimeric HAs were able to enter the cells.

**[0097]** **Fig. 9** describes the generation of recombinant viruses bearing chimeric hemagglutinins. (A) Western blot analysis of the recombinant viruses. Extracts from MDCK cells mock infected or infected with the indicated viruses (16 hpi) at an MOI of 2 were prepared and probed with antibodies: anti-A/PR8/HA(H1) (PY102), anti-A/Cal/09/HA(H1) (29C1), anti-A/VN/HA(H5) (M08), anti-H3/HA (12D1), anti-H7 (NR-3125), anti-A/NP (HT103) and anti-GAPDH as an internal loading control. (B) Immunofluorescence analysis of the MDCK cells infected with recombinant viruses using antibodies: anti-A/NP (HT103), anti-A/H1 HA (6F12), anti-A/PR8/HA (PY102), anti-A/Cal/09/HA (29C1), anti-A/VN/HA (M08), anti-H3/HA (12D1), and anti-A/H7 virus (NR-3152).

**[0098]** **Fig. 10** describes the growth kinetics and plaque phenotypes of recombinant viruses. (A) 10-day old embryonated chicken eggs were infected with wild-type or recombinant virus with 100 pfu per egg and viral growth monitored for 72 hours post infection. (B) The plaque phenotype of recombinant viruses was assessed by plaque assay. MDCK cells were infected with either a wild-type or recombinant virus and at 48 hours post infection immuno-stained to reveal plaque phenotype using the antibody against A/NP (HT103).

**[0099]** **Fig. 11** depicts an immunofluorescence analysis of cells transfected with chimeric H6 hemagglutinin. 293T cells were transfected with 1 μg of pCAGGS plasmid expressing chimeric H6 hemagglutinin. Sera from animals that received DNA (A), Cal/09 infection (B), DNA and Cal/09 infection (C), or Cal/09 split vaccine (D) were added to transfected cells and visualized by fluorescence microscopy following incubation with an Alexa Fluor 594-conjugated anti-mouse IgG.

**[00100]** **Fig. 12** demonstrates that DNA prime and chimeric virus boost confer protection to animals challenged with lethal influenza virus challenge. Animals were either treated with DNA alone, chimeric H9 virus alone, DNA prime and chimeric H9 virus boost, or with inactivated PR8 virus. Mice were then challenged with $5 \times 10^4$ PFU of PR8 virus, instilled intranasally, and the weight of the animals was monitored for 14 days.

**[00101]** **Fig. 13** demonstrates reactivity of stalk specific antibodies to cH6 protein as determined by ELISA.

**[00102]** **Fig. 14** depicts a schematic representation of chimeric HA (cHA) proteins (A) and cHA expression in MDCK cells (B). Chimeric HA (cHA) proteins and recombinant chimeric virus. (*A*) Schematic representation of cHAs. The globular head domain is defined as the intervening amino acid sequence between residues C52 and C277 (H3 numbering). Using this disulfide bond as the demarcation between head and stalk, exotic HA heads were introduced atop heterologous stalks. The stalk domain is defined as the remaining portions of HA1 and HA2 subunits. CT, cytoplasmic tail; SP, signal peptide; TM, transmembrane domain. The full-length HA structures were downloaded from the Protein Database (PDB): PR8 (H1) HA (PDB ID 1RU7) and A/guinea fowl/Hong Kong/WF10/99 HA [represented by A/swine/Hong Kong/9/98 (H9; PDB ID 1JSD)]. Final images were generated with PyMol (Delano Scientific). Because no structure of an H6 HA has been published, the image of the head-folding of the PR8 HA is used for the cH6/1 construct. (B) Immunofluorescence to confirm expression of cHA. MDCK cells were infected with either WT PR8 or cH9/1 N3 virus, or they were mock-infected. Antibodies specific for the head and stalk of PR8 virus as well as an antibody with H9 reactivity were used to confirm cHA expression. (Magnification bar: 40×).

**[00103]** **Fig. 15** shows that adult patients infected with pandemic H1N1 virus have high titers of neutralizing antibodies that are reactive with the HA stalk. Reactivity of sera of pH1N1-infected adults (n = 9), children not infected with pH1N1 (n = 5), and adults not infected with pH1N1 virus (n = 11) with cH6/1 protein (A), cH9/1 protein; (B), the LAH of the HA2 protein (anti-LAH antibody was used as a positive control; (C), H5 HA protein (mouse polyclonal serum raised against H5 HA was used as a positive control and a pan-H3 antibody, 12D1, was used as negative control; (D) (13), or H3 HA protein (12D1 was used as a positive control and mouse polyclonal serum raised against H5 HA was used as a negative control; (E). All were assessed by ELISA; data points represent average titers with SE or reactivity of pooled samples.

**[00104]** **Fig. 16** shows that adult patients infected with pandemic H1N1 virus have high titers of neutralizing antibodies that are specific for the HA stalk (A and B). Sera from pH1N1-infected ($n$ = 14) and adults not infected with pH1N1 ($n$= 5) were pooled separately, and total IgG from both pools was purified. Neutralizing capability of stalk antibodies was assessed by plaque reduction assay using cH9/1 N3 virus. Data points represent the mean and SE of two experiments. Plaques were immunostained with anti-H9 antibody G1-26. (B) shows plaque reduction of the four dilutions of sera shown along the top. (C) Pseudotype particle

neutralization assay measures neutralizing antibody activity of the human-purified IgG preparations (sera from pH1N1-infected adults and adults not infected with pH1N1). Total IgG concentrations were 50, 10, and 2 μg/mL. As a positive control, the stalk-specific monoclonal antibody 6F12 was used.

**[00105]** **Fig. 17** shows expression and function of cH6/1 and cH9/1 protein. A) Coomasie gel of 2 μg cH6/1 and cH9/1 protein. M, marker proteins. (B) Western blot analysis of baculovirus expressed cHA proteins. Lane 1, cH6/1 protein; lane 2, cH9/1 protein; lane 3, WT PR8 HA; lane 4, WT H3 HA. Blots were probed with antibodies known to react with the stalk of PR8 virus (rabbit polyclonal anti-HA2) or H3 viruses (mouse mAb 12D1) and the globular head of H6 (goat polyclonal anti-H6) or H9 viruses (mouse mAb G1-26) to confirm the identity of baculovirus expressed cHAs. mAb 12D1 reacts with both HA0 and HA2 (H3 protein preparation is cleaved, resulting in two distinct bands). (C) Plaque assay of cH9/1 N3 reassortant virus. Reassortant cH9/1 N3 virus plaque phenotype is similar to plaques made by WT PR8 virus. Plaques were immunostained with PY102 and anti-H9 antibody G1-26.

**[00106]** **Fig. 18** shows that monoclonal antibodies directed against the stalk of influenza virus HA bind and neutralize cHAs. (A) Stalk antibody C179 was used to test reactivity to cH6/1 baculovirus-expressed protein by ELISA. C179 reacted with cH9/1 in a dose-dependent manner. (B) Stalk antibody C179 was used to test reactivity to cH9/1 baculovirus-expressed protein by ELISA. C179 reacted with cH9/1 in a dose-dependent manner (C and D). Antibody 6F12 neutralizes cH9/1 N3 virus replication. 6F12 was used to assess the ability of stalk-specific monoclonal antibodies to neutralize cH9/1 N3 virus by plaque reduction assay. D shows plaque reduction of cH9/1 N3 virus using five dilutions of mAb 6F12 (100, 20, 4, 0.8, and 0.16 μg/mL). Plaques were immunostained with anti-H9 antibody G1-26.

**[00107]** **Fig. 19** depicts schematics of chimeric hemagglutinins. Fig. 19A shows a diagram of wild-type and cH1/1 viruses. The chimeric HA was constructed by swapping the globular head domain located between Cys52 and Cys277 of PR8 (H1) HA with that of the A/California/4/09 (H1) HA. The resulting chimeric HA has the stalk region of A/PR/8/34 (H1) HA with a globular head domain of the A/California/4/09 (H1) HA and is designated as cH1/1. Fig. 19B shows theoretical schematics of the folded structures of the different wild type and chimeric HAs. From left to right: wild type PR8 HA, the chimeric cH1/1 HA, the chimeric cH5/1 HA, the wild type Perth HA, the chimeric cH7/3 HA, and the chimeric cH5/3 HA.

**[00108]** **Fig. 20** depicts a table comparing amino acid identity between H1, H3, H5 and H7 HAs used in this study. Percent amino acid identity was calculated using ClustalW (excluding the signal peptide). Percent amino acid identity is compared for full length HA, as well as the globular head and stalk domains. Grey bars indicate 100% identity.

**[00109]** **Fig. 21** shows the surface expression of chimeric HA constructs. Surface expression of chimeric HA constructs was evaluated in transiently transfected or infected cells. At 48 h post-transfection, 293T cells were trypsinized and cell surface expression of chimeric HA proteins were analyzed by flow cytometry. In the upper panels, mock-transfected cells (grey) are compared to cells transfected with PR8 HA (black line) or cells transfected with cH1/1 (black line) or cH5/1 (black line). In the center panels, mock-transfected cells (grey) are compared to cells transfected with Perth/09, cH7/3 (black line) and cH5/3 constructs (black line). In the bottom panels, MDCK cells were infected with Perth/09, cH7/3 and cH5/3 expressing recombinant viruses. At 12 h post-infection the cell surface expression of the different HAs were analyzed using flow cytometry.

**[00110]** **Fig. 22** demonstrates the ability of the chimeric HAs to enter MDCK cells. Luciferase-encoding pseudoparticles expressing chimeric HAs were used to transduce MDCK cells. The relative light units (RLU) generated in the luciferase assay indicates that pseudoparticles expressing chimeric HAs are able to enter cells.

**[00111]** **Fig. 23** shows a Western blot analysis of cells infected with the recombinant cHA-expressing viruses. Extracts from MDCK cells mock infected or infected with the indicated viruses at an MOI of 2 were prepared and probed with antibodies at 16 hpi: anti-A/PR8/HA (H1) (PY102), anti-A/Cal/09/HA (H1) (29E3), anti-A/VN/HA (H5) (mAb #8), anti-H3/HA (12D1), anti-H7 (NR-3152), anti-A/NP (HT103) and anti-GAPDH as an loading control.

**[00112]** **Fig. 24** depicts an immunofluorescence analysis of MDCK cells infected with recombinant viruses using antibodies: anti-A/NP (HT103), anti-A/H1 HA (6F12), anti-A/PR8/HA (PY102), anti-A/Cal/09/HA (29E3), anti-A/VN/HA (mAb #8), anti-H3/HA (12D1), and anti-A/H7 virus (NR-3152).

**[00113]** **Fig. 25** depicts the growth kinetics and plaque phenotypes of wild type and recombinant viruses. (A) 10-day old embryonated chicken eggs were infected with 100 pfu per egg of wild-type or recombinant virus and viral growth was monitored for 72 hours post infection. Data points represent the average and standard deviation of experimental replicates.

(B) The plaque phenotypes of recombinant viruses were assessed by plaque assay. MDCK cells were infected with either a wild-type or recombinant virus. Cells were fixed 48 hours post infection and immunostained to reveal plaque phenotypes using the antibody against A/NP (HT103).

**[00114]** **Fig. 26** depicts that stalk-specific monoclonal antibody neutralizes cHA-expressing viruses and pseudotype particles. The ability of a mAb (KB2) to neutralize cHA-expressing viruses or pseudotype particles was assessed by plaque reduction assay or pseudotype particle inhibition assay. MDCK cells were infected or transduce with cHA-expressing viruses or pseudotype particles in the presence of the indicated amount (ug/mL) of the mAb or without antibody. Plaque formation or luciferase activity was used as a readout to determine the degree of inhibition by the mAb. The mAb neutralizes cH1/1 (black boxes) and cH5/1 (black triangles) virus replication in a dose dependent manner, with 100% inhibition at concentrations above 100 ug/mL. Data points represent the average and standard deviation of experimental replicates. (B) The mAb also inhibits entry of cH1/1 (black boxes) and cH5/1 (black triangles) pseudotype particles in a dose dependent manner, with complete inhibition above 4ug/mL. Data points represent the average and standard deviation of experimental replicates. The pseudotype inhibition assays were processed independently.

**[00115]** **Fig. 27** demonstrates that sequential vaccination with cHA constructs elicits HA stalk-specific antibodies and provides protection from lethal challenge. Mice were primed with 20 μg of cH9/1 protein, administered with adjuvant intranasally and intraperitoneally. Three weeks later, mice were boosted with 20 μg cH6/1 protein, administered with adjuvant intranasally and intraperitoneally. As controls, mice were primed and boosted in a similar fashion using BSA, or given inactivated FM1 virus intramuscularly. Animals were bled and challenged three weeks after the last vaccination with 5LD50 of A/Fort Monmouth/1/1947 (FM1) virus. (A) ELISA plates were coated with cH5/1 N1 virus in order to assess the degree of stalk reactivity elicited through vaccination (BSA + BSA is the bottom line of the graph). (B) Mice were weighed daily for 14 days to assess protection from challenge. (C) Kaplan Meier curve depicting survival rate post challenge. cH9/1 + cH6/1 vaccinated mice had a statistically higher survival rate compared to BSA controls ($p = .0003$)

**[00116]** **Fig. 28** demonstrates that vaccination with cH6/1 elicits stalk-specific immunity that mediates protection from cH9/1 N1 viral challenge. Animals were inoculated with YAM-HA

virus in order to simulate prior infection with or vaccination against influenza virus. Three weeks later, animals were vaccinated with cH6/1 or BSA with adjuvant, intranasally and intraperitoneally. Control animals were inoculated with wild-type B/Yamagata/16/1988 and vaccinated in a similar fashion with BSA, or given inactivated cH9/1 N1 virus intramuscularly. Animals were bled and challenged with 250$LD_{50}$ cH9/1 N1 virus three weeks after vaccination. (A) Animals were weighed for 8 days in order to assess protection from challenge. On days 3-5, YAM-HA + cH6/1 animals demonstrated statistically less weight loss compared to the YAM-HA + BSA cohort ($p < .05$). (B) Kaplan Meier curve depicting survival. Statistically different survival rates were seen in the YAM-HA + cH6/1 group compared to the YAM-HA + BSA cohort ($p = .038$), as well as naïve and WT YAM + BSA animals ($p < .0001$). Survival rate of YAM-HA + BSA cohort was not statistically different from that of the WT-YAM + BSA cohort ($p = 0.058$). (C) ELISA plates were coated with cH5/1 N1 virus in order to assess the degree of stalk reactivity elicited through vaccination. (D) Results of a plaque reduction assay using the cH5/1 virus are depicted. (E) Animals were vaccinated, bled and total IgG was harvested for H5-based pseudoparticle entry inhibition assay. Percent inhibition was assessed as a decrease in luciferase expression compared to controls.

**[00117]** **Fig. 29** demonstrates that vaccination with cH6/1 protects mice from lethal H5 influenza virus challenge. Animals were inoculated with YAM-HA virus in order to simulate prior infection with or vaccination against influenza virus. Three weeks later, animals were vaccinated with cH6/1 or BSA with adjuvant, intranasally and intraperitoneally. Control animals were inoculated with wild-type B/Yamagata/16/1988 and vaccinated in a similar fashion with BSA or given inactivated cH5/1 N1 virus intramuscularly. Animals were bled and challenged with 10$LD_{50}$ of the 2:6 H5 reassortant in the PR8 background (see, e.g., Steel et al., 2009, J Virol 83:1742-1753). (A) Kaplan Meier curve depicting survival. Differences in survival rates approached statistical significance when comparing the YAM-HA+cH6/1 group to the YAM-HA+BSA cohort ($p = .06$). (B) Length of survival was on average longer in animals inoculated with YAM-HA and vaccinated with cH6/1 than animals vaccinated with BSA ($p = 0.037$), as well as naïve and WT YAM/BSA controls ($p < 0.001$). (C) ELISA plates were coated with cH5/1 N1 virus in order to assess the degree of stalk reactivity elicited through vaccination. 1:50 serum dilutions were plotted against % maximum weight loss. One value was determined to be an outlier and was omitted from analysis. For linear regression, $R^2 = 0.56$ and $p = .02$.

**[00118]** **Fig. 30** demonstrates that vaccination with cHA elicits stalk-specific immunity that mediates protection from H1N1 virus challenge. (A-F) Animals were primed with DNA encoding cH9/1 and then were vaccinated with cH6/1 and boosted with cH5/1 soluble protein (n=10) or BSA (n=5), while positive control mice received inactivated virus intramuscularly (n=5). (A) Animals were vaccinated and challenged with FM1 virus; mice were weighed daily, and weight loss over time is shown as change in percentage of initial weight. (B) Graph depicting survival of challenged mice in (A). (C) Animals were vaccinated and challenged with pH1N1 virus; mice were weighed daily, and weight loss over time is shown as change in percentage of initial weight. (D) Graph depicting survival of challenged mice in (C). (E) Animals were vaccinated and challenged with PR8 virus; mice were weighed daily, and weight loss over time is shown as change in percentage of initial weight. (F) Graph depicting survival of challenged mice in (E). (G) Reactivity to H1 HA of serum from animals vaccinated as described above in A-F and below in H-I and challenged with 5 $LD_{50}$ of A/FM/1/1947 (A, B), 10 $LD_{50}$ of A/Netherland/602/2009 (C, D), or 5 $LD_{50}$ of A/PR/8/1934 (E, F, H, I). (H) Animals were vaccinated as described above in A-F (square, n=4) or were naive (triangle, n=3), while positive control mice received inactivated PR8 virus intramuscularly (X mark, n=5). CD8 T cells were depleted prior to challenge with PR8 virus. Mice were weighed daily, and weight loss over time is shown as change in percentage of initial weight. (I) Graph depicting survival of challenged mice in (H). (J) Animals were vaccinated as described for A-F. Total IgG was purified for use in H2-based pseudoparticle entry inhibition assay. Percent inhibition was assessed as a decrease in luciferase expression compared to controls. Fab fragment CR6261 was used as a positive control.

**[00119]** **Fig. 31.** Schematic of wild type HA and expression constructs. (A) Uncleaved full length influenza virus hemagglutinin. The signal peptide is the leftmost component, the HA ectodomain is the middle component and the transmembrane- and endodomain are the rightmost component. (B) Expression construct with trimerization domain. The transmembrane- and endodomain was swapped with a thrombin cleavage site (third component from left), a T4 trimerization domain (fourth component from left) and a hexahistidine tag (6xhis tag, fifth component from left) at position V503 (H3 numbering). (C) Expression construct without trimerization domain. The transmembrane- and endodomain was swapped with a hexahistidine

tag (6xhis tag, rightmost component) at amino acid position 509 (H1, H2 and H5) or 508 (H3) respectively (H3 numbering).

**[00120]** **Fig. 32.** Introduction of a trimerization domain influences stability and formation of oligomers in recombinant HAs. (A) Analysis of recombinant HAs with and without trimerization domain by reducing, denaturing SDS-PAGE. Recombinant HAs that are expressed with trimerization domain (+) show higher stability than HAs expressed without (-). Uncleaved HA (HA0) and cleavage products (HA1/degr. product; HA2) are indicated by arrows. (B) Reducing, denaturing SDS-PAGE analysis of crosslinked HAs. Different species of HA are indicated in the blot. High molecular multimers are indicated by H, trimers by T, dimers by D and monomers by M. (C) Left panel (boxes 1-4): Western blot analysis of reduced, denatured and cross-linked group 1 HAs from B probed with a anti-hexahistidine-tag antibody. Right panel (rightmost box): Cross-linking control (IgG) with $BS^3$ analyzed on a SDS-PAGE. Different species (full antibody, heavy chain, light chain) are indicated by arrows. Molecular weights of the marker bands are indicated on the left of each panel.

**[00121]** **Fig. 33.** Binding of stalk-reactive antibodies to recombinant PR8 (H1) and Cal09 (H1) HAs. (A) Binding of stalk-reactive antibodies C179, CR6261 and 6F12 and head-reactive antibody PY102 and PR8 antiserum to recombinant soluble PR8 HA without (w/o T4 trim. domain, triangle lines) or with (w/ T4 trim. domain, boxed lines) trimerization domain. (B) Binding of stalk-reactive antibodies C179, CR6261 and 6F12 and head-reactive antibody 7B2 and Cal09 antiserum to recombinant soluble Cal09 HA without (w/o T4 trim. domain, triangle lines) or with (w/ T4 trim. domain, boxed lines) trimerization domain.

**[00122]** **Fig. 34.** Binding of stalk-reactive antibodies to recombinant JAP57 (H2) and VN04 (H5) HAs. (A) Binding of stalk-reactive antibodies C179 and CR6261 and head-reactive antibody 8F8 and H2 antiserum to recombinant soluble JAP57 HA without (w/o T4 trim. domain, triangle lines) or with (w/ T4 trim. domain, boxed lines) trimerization domain. (B) Binding of stalk-reactive antibodies C179 and CR6261 and head-reactive antibody mAb#8 and H5 antiserum to recombinant soluble VN04 HA without (w/o T4 trim. domain, triangle lines) or with (w/ T4 trim. domain, boxed lines) trimerization domain.

**[00123]** **Fig. 35.** Binding of stalk-reactive antibodies to group 2 HAs. (A) Binding of stalk-reactive antibodies 12D1 and CR8020 and head-reactive antibody XY102 and H3 antiserum to recombinant soluble HK68 HA without (w/o T4 trim. domain, triangle lines) or with (w/ T4 trim.

domain, boxed lines) trimerization domain. (B) Binding of stalk-reactive antibodies 12D1 and CR8020 and H3 antiserum to recombinant soluble Wisc05 HA without (w/o T4 trim. domain, triangle lines) or with (w/ T4 trim. domain, boxed lines) trimerization domain.

**[00124]** **Fig. 36** depicts an exemplary chimeric influenza virus hemagglutinin polypeptide (SEQ ID NO: 21) comprising the stem domain of an influenza B virus (B/Florida/4/2006) and the globular head domain of an influenza A virus of the H5 subtype (A/Vietnam/1203/2004).

**[00125]** **Fig. 37** demonstrates that an HA stalk-based vaccination strategy provides broad protection from challenge with divergent H3N2 viruses. (A) Schematic representation of the vaccination strategy (the monomeric form of each antigen is shown). (B to E) Animals were vaccinated with plasmid DNA coding for cH4/3 HA and subsequently boosted with recombinant soluble cH5/3, followed by cH7/3 proteins (grey triangles, point down; n = 9 or 10 animals). Positive-control animals received inactivated vaccine containing the matched challenge strain (grey circles; n = 5 animals). Prime-only animals (grey triangles, point up; n = 5 animals) received the DNA prime followed by two irrelevant protein boosts. Naive animals (black squares; n = 5 animals) were used as additional controls for challenge. (B) Weight loss curves upon challenge with the Phil82 (H3N2) virus. (C) Kaplan-Meier survival curve upon Phil82 challenge. (D) Morbidity observed upon challenge with the X-31 (H3N2) virus. (E) Survival curves following the X-31 (H3N2) challenge. Survival of vaccinated (cH4/3DNA-cH5/3-cH7/3) versus control (cH4/3DNA-BSA-BSA) groups is highly significant for both challenge experiments (P = 0.0008 and 0.0001, respectively). (F and G) Lung titration experiments to further test the protection breadth of the vaccine against viruses that are not lethal in the mouse model. Vaccinated animals (BcH7/3-cH5/3-cH4/3) and control animals (Bwt-BSA- BSA) were infected with 5 X $10^4$ PFU of H3N2 variant (F) or 1 X $10^5$ PFU of the human H3N2 A/Wyoming/03/03 (G). On day 3 postinfection, lungs of animals from both groups were harvested and homogenized, and the 50% tissue culture infectious dose ($TCID_{50}$) was measured.

**[00126]** **Fig. 38** shows vaccination with cHA constructs can boost preexistent titers of stalk-reactive antibodies to protective levels. (A to G) To mimic the preexisting immunity to the stalk domain present in the human population, animals were sublethaly infected with a recombinant influenza B virus that expresses cH7/3 HA. Subsequently, they were boosted with recombinant soluble cH5/3 (or full-length H3 HA for cH5/3N1-challenged animals) and then cH4/3 protein (dark-grey triangles, point down; n = 10 animals). Positive-control animals received inactivated

vaccine containing the matched challenge strain (dark-grey circles; n = 5 animals). Prime-only animals (dark-grey triangles, point up; n = 5 animals) received the recombinant influenza B prime and then two irrelevant protein boosts. Additional control groups were either infected with wild-type influenza B virus and then received two irrelevant protein boosts (light-grey triangles, point down; n = 5) or were naive (black squares; n = 5). (B to D) Weight loss curves following viral challenges. (B) A mouse-pathogenic cH5/3N1 virus which expresses the stalk domain of an HA from a recent human H3N2 isolate as the surrogate challenge strain was used to test efficacy against contemporary stalk domains, since modern human H3N2 isolates are not pathogenic in mice. Weight loss upon infection with the X-31 (H3N2; HA and NA from A/Hong Kong/1/68) (C) and Phil82 (H3N2) (D) viruses; (E) Kaplan-Meier survival curve following the A/cH5/3N1 challenge; (F) survival curves following the Phil82 (H3N2) challenge; (G) survival curves following the X-31 (H3N2) challenge. Statistical analysis revealed high significance for all challenges when comparing BcH7/3-cH5/3-cH4/3 and BcH7/3-BSA-BSA groups ($P = 0.082$, $P < 0.0001$, and $P < 0.0001$).

**[00127]** **Fig. 39** demonstrates that the elicited anti-stalk responses are cross-reactive against multiple H3N2 strains, including the most recent vaccine strain. The elicited anti-stalk responses are cross-reactive against multiple H3N2 strains, including the most recent vaccine strain. (A to E) ELISA reactivity against Phil82 (H3N2, whole virus) (A), X-31 virus (H3N2; expressing HA and NA from A/Hong Kong/1/68 virus) (B), H3N8 virus (C), the current influenza vaccine strain Vic11 (H3N2, virus) (D), or Perth09 protein (H3) (E) of sera collected from animals vaccinated with cHA constructs (dark-grey triangles, point down, cH4/3DNA-cH5/3-cH7/3), prime-only animals (dark-grey triangles,point up), or naive animals (black squares). (F to H) ELISA reactivity against Vic11 H3N2 (F) or Phil82 H3N2 (G) or X-31 H3N2 (H) virus of sera collected from animals vaccinated with cHA constructs (dark grey triangles, point down, B/cH7/3 virus-cH5/3 protein-cH4/3 protein), prime-only animals (dark-grey triangles, point up), control animals that were infected with wild-type influenza B virus and then received two BSA boosts (light-grey triangles, point down), or naive animals (black squares).

**[00128]** **Fig. 40** demonstrates that the breadth of the anti-H3 HA stalk antibodies elicited by the cHA vaccination strategy extends to other members of the group 2 HAs, including the most recent Chinese H7N9 virus. (A) The vaccination scheme presented in Fig. 37 was modified to ensure that anti-H7 globular-head domain antibodies are not involved in the effects observed in

this series of experiments. Animals received the same prime (DNA coding for cH4/3 HA) and first boost (cH5/3 protein), but the second boost was replaced with an H3 protein (cH4/3DNA-cH5/3-H3; grey triangles, point up, n = 10 animals). Positive-control animals received inactivated Rhe$^{a}$H7 virus vaccine (grey circles, n = 5). Prime-only animals (grey triangles, point up, n = 5 animals) received the DNA prime followed by two irrelevant protein boosts. Naive animals (black squares, n = 5 animals) were used as additional controls. (B) Weight loss curve upon challenge with RheaH7 (H7N1) virus. (C) Kaplan-Meier survival curve. The vaccine provided good protection against mortality (P = 0.0088, cH4/3DNA-cH5/3-cH7/3 versus controls cH4/3DNA-BSA-BSA). (D, E) ELISA reactivity of sera from vaccinated animals (grey triangles, point down, cH4/3DNA-cH5/3-cH7/3), co*ntrol a*nimals *(grey t*riangles, point up, cH4/3DNA-BSA-BSA), or naive mice (black squares) to RheaH7 virus (D) or the HA protein expressed by the recent Shanghai13 H7N9 (E) virus. (F) Mice that received the vaccine (BcH7/3-cH5/3-cH4/3) and controls (Bwt-BSA-BSA) were infected with with 1 X $10^5$ PFU of H10N7 virus and measured a 20-fold decrease in viral TCID50 in the lungs of vaccinated mice on day 3 postinfection. (G) Sera collected from vaccinated mice cH4/3DNA-cH5/3-H3 recognize a panel of group 2 HA proteins. MDCK cells were transfected with plasmids encoding the respective HA and were fixed 16 h later with 0.5% paraformaldehyde. Reactivity was detected by immunofluorescence with sera from mice that received the vaccine. Serum collected from naive animals was used as a negative control. A mouse (FBE9 [unpublished, generated in-house]) and a human (FI6) (Corti *et al.,* 2011, *Science* 333:850-856.) monoclonal anti-stalk antibody were used as positive controls.

**[00129]** **Fig. 41** shows that the polyclonal responses elicited by the chimeric HA vaccination are directed against the stalk domain and neutralize virus infection both *in vitro* and *in vivo*. (A) An ELISA against a group 1 HA protein (H1) demonstrates that the cross-reactive responses elicited by the cHA vaccine (dark-grey triangles, point down, B/cH7/3-cH5/3-cH4/3) are not directed against conserved parts of the receptor binding site in the HA protein. (B) ELISA reactivity of nasal washes from animals vaccinated with cHA constructs (dark-grey triangles, point down, B/cH7/3-cH5/3 protein-cH4/3 protein), prime-only animals (light-grey triangles, point up, B/cH7/3-irrelevant protein-irrelevant protein), vector controls (light-grey triangles, point down, Bwt-irrelevant protein-irrelevant protein), and naive animals (black squares). (C) Antibody isotypes in sera from vaccinated (B/cH7/3 virus-cH5/3 protein-cH4/3 protein), naive,

prime-only (B/cH7/3 virus-BSA-BSA), and vector control animals (Bwt virus-BSA-BSA). (D) Vic11 (H3) pseudotyped particle neutralization assay with sera from cHA-vaccinated animals (dark-grey triangles, point down, B/cH7/3-cH5/3-cH4/3), vector controls (light-grey triangles, point down, Bwt-irrelevant protein-irrelevant protein), and naive animals (black squares). The reciprocal serum dilution is shown on the x axis. An H3 stalk-reactive monoclonal antibody (12D1) was used as positive control (grey circles), at a starting concentration of 123 μg/ml. (E) Passive transfer challenge experiment (Phil82 H3N2 virus) with sera from animals that were vaccinated (dark-grey triangles, point down, BcH7/3-cH5/3-cH4/3, n = 5 animals), vector controls (light-grey triangles, point down, Bwt-BSA-BSA, n = 5 animals), naive animals (black squares, n = 5 animals), and positive-control animals (received inactivated Phil82 virus vaccine, n = 5 animals). Kaplan-Meier survival curve is shown ($P < 0.026$ for BcH7/3-cH5/3-cH4/3 versus Bwt-BSA-BSA groups).

**[00130]** **Fig. 42** shows phylogeny of select members of group 2 influenza virus hemagglutinins depicting the breadth of the response elicited by the vaccine. The protein sequences were downloaded from GenBank, and multiple alignments were performed using the ClustalW algorithm in Mega version 5.1. Phylogenetic trees were constructed using the FigTree software and the neighbor-joining method. The scale bar represents a 5% amino acid change. Positively tested cross-protection/cross-reactivity of cHA-vaccinated mice to the respective strains is indicated in parenthesis after the strain names (immunofluorescence [IF], challenge, ELISA, and lung titer). Strain names without indication were not tested.

**[00131]** **Fig. 43** reveals vaccination with H3 stalk-based cHA protects mice from challenge with H7N9 virus. (A) Schematic representation of the vaccination regimen. Structures are based on protein database structure # 1RU7. Mice in (B-G) received a DNA prime coding for cH4/3 protein (H4 head in combination with and H3 stalk) and were then boosted with cH5/3 (H5 head on top of an H3 stalk) and full length H3 protein. The animals were challenged four weeks after the last immunization with H7N9 virus. Weight loss curves are shown in (B-D), survival curves are shown in (E-G). The dashed line in (C and D) indicates the highest average weight loss (day 7) of the 'PIC i.n.+i.m.' group shown in (B). Mice shown in (B) and E (PIC i.n.+i.m.) were boosted sequentially with cH4/3 and cH5/3 protein intranasally and intramuscularly in the presence of polyI:C as adjuvant. Animals in (C) and (F) received the same proteins as boost but received the immunizations only intramuscularly (PIC i.m.). Mice in (D) and (G) were

immunized intramuscularly only with an oil-in-water adjuvant (OIW i.m.). Animals in the control groups received BSA with the respective adjuvant and via the respective routes. Positive control animals (same group was compared to all three experimental conditions) were vaccinated intramuscularly with inactivated matched challenge virus.

**[00132]** **Fig. 44** depicts oil-in-water (OIW) adjuvant preparation and characteristics. (A) Scheme of the OIW adjuvant preparation. The OIW emulsion is prepared at 20-40 mL scale. Span-85 is dissolved in squalene, polysorbate 80 is dissolved deionized water and then mixed with citrate-citric acid buffer. Oil and aqueous phase fractions are combined and mixed into a coarse emulsion by vortexing which is then passed through an LV1 Microfluidizer (Microfluidics, Westwood, MA) at 12,000 psi. The eluent is collected and re-passaged for a total of 5 passes through the microfluidizer to yield a stable and homogeneous emulsion. The final pass is filtered through 0.22μm filter and filled into sterile glass vials. (B) Particle size of the OIW adjuvant prepared by microfluidization was determined by dynamic light scattering on a Malvern Nano 3ZS. The sizes shown are the Z-average mean from 2 independently prepared batches. These preparations are considered monomodal as polydispersity after the final passage through the microfluidizer and sterile filtration ranged from 8-11%.

**[00133]** **Fig. 45** illustrates vaccination with H3 stalk-based cHAs induces high antibody titers against H7 hemagglutinin in mice. (A) IgG endpoint titers of cHA vaccinated mice against H7 (A/Shanghai/1/13) HA. The one-tailed p value was calculated using an unpaired t test. (B) Immunoglobulin isotype distribution directed to H7 HA in sera from mice vaccinated via different routes and with different adjuvants. The analysis was performed at a 1:200 dilution.

## 5. DETAILED DESCRIPTION

**[00134]** In one aspect, provided herein are chimeric influenza hemagglutinin (HA) polypeptides that induce a cross-protective immune response against the conserved HA stem domain of influenza viruses. The chimeric influenza HA polypeptides provided herein comprise a stable HA stem domain and a globular HA head domain that is heterologous to the stem domain (i.e. the head and stem domains are derived from different strains and/or subtypes of influenza virus).

**[00135]** In another aspect, provided herein are compositions comprising one or more of the chimeric influenza hemagglutinin polypeptides described herein (e.g., compositions comprising soluble chimeric influenza hemagglutinin polypeptides described herein, viruses comprising the chimeric influenza hemagglutinin polypeptides described herein, viruses comprising genomes engineered to encode the chimeric influenza hemagglutinin polypeptides described herein, expression vectors comprising the chimeric influenza hemagglutinin polypeptides described herein, expression vectors comprising genomes engineered to encode the chimeric influenza hemagglutinin polypeptides described herein, nucleic acids encoding the chimeric influenza hemagglutinin polypeptides described herein, etc.).

**[00136]** In another aspect, provided herein are vaccine formulations comprising one or more of the chimeric influenza hemagglutinin polypeptides described herein. In a specific embodiment, provided herein is a monovalent vaccine comprising one of the chimeric influenza hemagglutinin polypeptides described herein. In another specific embodiment, provided herein is a bivalent vaccine comprising two of the chimeric influenza hemagglutinin polypeptides described herein (i.e., two distinct chimeric influenza hemagglutinin polypeptides). In another specific embodiment, provided herein is a trivalent vaccine comprising three of the chimeric influenza hemagglutinin polypeptides described herein (i.e., three distinct chimeric influenza hemagglutinin polypeptides). The vaccine formulations provided herein may comprise, for example, subunit vaccines comprising one or more of the chimeric influenza hemagglutinin polypeptides described herein (e.g., compositions comprising chimeric influenza hemagglutinin polypeptides, e.g., soluble chimeric influenza hemagglutinin polypeptides); live influenza viruses (e.g., live attenuated influenza viruses) that express one or more of the chimeric influenza hemagglutinin polypeptides described herein; live influenza viruses (e.g., live attenuated influenza viruses) comprising a genome that encodes one or more of the chimeric influenza hemagglutinin polypeptides described herein; killed influenza viruses that express one or more of the chimeric influenza hemagglutinin polypeptides described herein; killed influenza viruses comprising a genome that encodes one or more of the chimeric influenza hemagglutinin polypeptides described herein; virus/viral-like particles ("VLPs") that contain one or more of the chimeric influenza hemagglutinin polypeptides described herein; split virus vaccines, wherein said virus expresses one or more of the chimeric influenza hemagglutinin polypeptides described herein and/or comprises a genome that encodes one or more of the chimeric influenza

hemagglutinin polypeptides described herein; viral expression vectors (e.g., non-influenza virus expression vectors) that express one or more of the chimeric influenza hemagglutinin polypeptides described herein; and bacterial expression vectors that express one or more of the chimeric influenza hemagglutinin polypeptides described herein.

**[00137]** The vaccine formulations described herein can elicit highly potent and broadly neutralizing antibodies against the HA stem domain of the chimeric influenza hemagglutinin polypeptides. Such "universal" vaccines can be used to induce and/or boost cross-protective immune responses across influenza virus subtypes.

**[00138]** In another aspect, provided herein are methods of immunizing a subject against an influenza virus disease or infection comprising administering to the subject a composition comprising one or more of the chimeric influenza hemagglutinin (HA) polypeptides described herein or a vaccine formulation described herein.

**[00139]** In another aspect, provided herein are kits comprising one or more of the chimeric influenza hemagglutinin (HA) polypeptides described herein or a vaccine formulation described herein. The kits provided herein may further comprise one or more additional components, e.g., an antibody that specifically binds one or more of the chimeric influenza hemagglutinin (HA) polypeptides provided in the kit.

## 5.1 CHIMERIC INFLUENZA VIRUS HEMAGGLUTININ POLYPEPTIDES

**[00140]** Provided herein are chimeric influenza virus hemagglutinin polypeptides comprising or consisting of an influenza virus hemagglutinin globular head domain polypeptide and an influenza virus hemagglutinin stem domain polypeptide, wherein said influenza virus hemagglutinin head domain polypeptide is heterologous to said influenza virus hemagglutinin stem domain polypeptide (e.g., the influenza virus hemagglutinin globular head domain polypeptide and the influenza virus hemagglutinin stem domain polypeptide are derived from different influenza virus hemagglutinin subtypes). The stem and globular head domains of a chimeric influenza virus hemagglutinin polypeptide can be based on influenza A virus hemagglutinin stem and globular head domains (e.g. H1, H2, H3, H4, H5, H6, H7, H8, H9, H10, H11, H12, H13, H14, 15, H16, H17, and H18) and/or influenza B virus hemagglutinin stem and globular head domains.

**[00141]** A full-length influenza hemagglutinin typically comprises an HA1 domain and an HA2 domain. The stem domain is formed by two segments of the HA1 domain and most or all of the HA2 domain. The two segments of the HA1 domain are separated, in primary sequence, by the globular head domain (see, e.g., the amino acid residues between the residues designated $A_p$ and $A_q$ in Figure 1). In certain embodiments, the chimeric influenza virus hemagglutinin polypeptides described herein maintain such a structure. That is, in certain embodiments, the chimeric influenza virus hemagglutinin polypeptides described herein comprise a stable stem structure composed of an HA1 domain and an HA2 domain, and a globular head domain separating the two segments of the HA1 domain (in primary sequence), wherein said globular head domain is heterologous to the stem domain formed by the other segments of the HA1 domain and the HA2 domain.

**[00142]** In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide provided herein comprises (i) the stem domain of the hemagglutinin from an influenza virus of the H1 subtype and (ii) the globular head domain of the hemagglutinin from an influenza virus of the H5 subtype (sometimes referred to herein as a "cH5/1 chimeric influenza hemagglutinin polypeptide"). In a specific embodiment, the stem domain of a cH5/1 chimeric influenza hemagglutinin polypeptide is the stem domain of A/California/4/2009 (H1N1) HA (or the stem domain of an A/California/4/2009-like influenza virus HA). In another specific embodiment, the stem domain of a cH5/1 chimeric influenza hemagglutinin polypeptide is the stem domain of A/California/4/2009 (H1N1) HA (or the stem domain of an A/California/4/2009-like influenza virus HA) and the globular head domain of the cH5/1 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA. In another specific embodiment, the stem domain of a cH5/1 chimeric influenza hemagglutinin polypeptide is the stem domain of A/California/4/2009 (H1N1) HA (or the stem domain of an A/California/4/2009-like influenza virus HA) and the globular head domain of the cH5/1 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/1 chimeric influenza hemagglutinin polypeptide is the stem domain of A/California/4/2009 (H1N1) HA (or the stem domain of an A/California/4/2009-like influenza virus HA) and the globular head domain of the cH5/1 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/1 chimeric influenza

hemagglutinin polypeptide is the stem domain of A/California/4/2009 (H1N1) HA (or the stem domain of an A/California/4/2009-like influenza virus HA) and the globular head domain of the cH5/1 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/1 chimeric influenza hemagglutinin polypeptide is the stem domain of A/California/4/2009 (H1N1) HA (or the stem domain of an A/California/4/2009-like influenza virus HA) and the globular head domain of the cH5/1 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/1 chimeric influenza hemagglutinin polypeptide is the stem domain of A/California/4/2009 (H1N1) HA (or the stem domain of an A/California/4/2009-like influenza virus HA) and the globular head domain of the cH5/1 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA.

**[00143]** In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide provided herein comprises (i) the stem domain of the hemagglutinin from an influenza virus of the H3 subtype and (ii) the globular head domain of the hemagglutinin from an influenza virus of the H5 subtype (sometimes referred to herein as a "cH5/3 chimeric influenza hemagglutinin polypeptide"). In a specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA and the

globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA.

**[00144]** In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor

seal/Massachusetts/1/2011 (H3N8) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA.

**[00145]** In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA.

**[00146]** In a specific embodiment, a cH5/3 chimeric influenza hemagglutinin polypeptide provided herein does not comprise the globular head domain of A/Vietnam/1203/2004 (H5) HA. In another specific embodiment, a cH5/3 chimeric influenza hemagglutinin polypeptide does not comprise the stem domain of A/Perth/16/2009 (H3) HA.

**[00147]** In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA and the globular head domain of the cH5/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA.

**[00148]** In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide provided herein comprises (i) the stem domain of the hemagglutinin from an influenza virus of the H3 subtype and (ii) the globular head domain of the hemagglutinin from an influenza virus of the H7 subtype (sometimes referred to herein as a "cH7/3 chimeric influenza hemagglutinin polypeptide"). In a specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA and the globular head domain of the

cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Netherlands/219/03 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/504/04 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/444/04 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/chicken/Jalisco/CPA1/2012 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Alberta/24/2001 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/rhea/NC/39482/93 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Victoria/361/2011 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Netherlands/12/2000 (H7) HA.

**[00149]** In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Netherlands/219/03 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/504/04

(H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/444/04 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/chicken/Jalisco/CPA1/2012 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Alberta/24/2001 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/rhea/NC/39482/93 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/harbor seal/Massachusetts/1/2011 (H3N8) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Netherlands/12/2000 (H7) HA.

**[00150]** In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Netherlands/219/03 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/504/04 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/444/04 (H7) HA. In

another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/chicken/Jalisco/CPA1/2012 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Alberta/24/2001 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/rhea/NC/39482/93 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Indiana/10/2011 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Netherlands/12/2000 (H7) HA.

**[00151]** In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Netherlands/219/03 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/504/04 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/444/04 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/chicken/Jalisco/CPA1/2012 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009

(H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Alberta/24/2001 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/rhea/NC/39482/93 (H7) HA. In another specific embodiment, the stem domain of a cH7/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/2009 (H3N2) HA and the globular head domain of the cH7/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Netherlands/12/2000 (H7) HA.

**[00152]** In a specific embodiment, a cH7/3 chimeric influenza hemagglutinin polypeptide provided herein does not comprise the globular head domain of A/mallard/Alberta/24/2001 (H7) HA. In another specific embodiment, a cH7/3 chimeric influenza hemagglutinin polypeptide does not comprise the stem domain of A/Perth/16/2009 (H3) HA.

**[00153]** In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide provided herein comprises (i) the stem domain of the hemagglutinin from an influenza B virus and (ii) the globular head domain of the hemagglutinin from an influenza virus of the H5 subtype (sometimes referred to herein as a "cH5/B chimeric influenza hemagglutinin polypeptide"). In a specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA and the globular head domain of the cH5/B chimeric influenza

hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA.

**[00154]** In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA.

**[00155]** In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Indonesia/5/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA.

**[00156]** In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Vietnam/1203/2004 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain

of A/Indonesia/5/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Anhui/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/bar headed goose/Quinghai/1A/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/turkey/Turkey/1/2005 (H5) HA. In another specific embodiment, the stem domain of a cH5/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA and the globular head domain of the cH5/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/whooperswan/Mongolia/244/2005 (H5) HA.

**[00157]** In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide provided herein comprises (i) the stem domain of the hemagglutinin from an influenza B virus and (ii) the globular head domain of the hemagglutinin from an influenza virus of the H7 subtype (sometimes referred to herein as a "cH7/B chimeric influenza hemagglutinin polypeptide"). In a specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Netherlands/219/03 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/504/04 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/444/04 (H7) HA. In another specific embodiment, the stem

domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/chicken/Jalisco/CPA1/2012 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Alberta/24/2001 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/rhea/NC/39482/93 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Netherlands/12/2000 (H7) HA.

**[00158]** In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Netherlands/219/03 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/504/04 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/444/04 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/chicken/Jalisco/CPA1/2012 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA and the globular head

domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Alberta/24/2001 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/rhea/NC/39482/93 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Netherlands/12/2000 (H7) HA.

**[00159]** In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Netherlands/219/03 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/504/04 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/444/04 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/chicken/Jalisco/CPA1/2012 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Alberta/24/2001 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/rhea/NC/39482/93 (H7) HA. In another specific embodiment, the

stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Netherlands/12/2000 (H7) HA.

**[00160]** In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Netherlands/219/03 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/504/04 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/Canada/444/04 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/chicken/Jalisco/CPA1/2012 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Alberta/24/2001 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/rhea/NC/39482/93 (H7) HA. In another specific embodiment, the stem domain of a cH7/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA and the globular head domain of the cH7/B chimeric influenza hemagglutinin polypeptide is the globular head domain of A/mallard/Netherlands/12/2000 (H7) HA.

**[00161]** In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide provided herein comprises (i) the stem domain of the hemagglutinin from an influenza B virus and (ii) the globular head domain of the hemagglutinin from a different influenza B virus strain (sometimes referred to herein as a "cB/B chimeric influenza hemagglutinin polypeptide"). In a specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA. In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA and the globular head domain of the cB/B chimeric influenza hemagglutinin polypeptide is the globular head domain of B/Lee/1940 HA. In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Malaysia/2506/2004 HA and the globular head domain of the cB/B chimeric influenza hemagglutinin polypeptide is the globular head domain of B/seal/Netherlands/1/99 HA (or a B/seal/Netherlands/1/99-like influenza virus).

**[00162]** In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA. In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA and the globular head domain of the cB/B chimeric influenza hemagglutinin polypeptide is the globular head domain of B/Lee/1940 HA. In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Florida/4/2006 HA and the globular head domain of the cB/B chimeric influenza hemagglutinin polypeptide is the globular head domain of B/seal/Netherlands/1/99 HA (or a B/seal/Netherlands/1/99-like influenza virus).

**[00163]** In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA. In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA and the globular head domain of the cB/B chimeric influenza hemagglutinin polypeptide is the globular head domain of B/Lee/1940 HA. In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Wisconsin/1/2010 HA and the globular head domain of the cB/B chimeric influenza hemagglutinin polypeptide is the globular head domain of B/seal/Netherlands/1/99 HA (or a B/seal/Netherlands/1/99-like influenza virus).

**[00164]** In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA. In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA and the globular head domain of the cB/B chimeric influenza hemagglutinin polypeptide is the globular head domain of B/Lee/1940 HA. In another specific embodiment, the stem domain of a cB/B chimeric influenza hemagglutinin polypeptide is the stem domain of B/Brisbane/60/2008 HA and the globular head domain of the cB/B chimeric influenza hemagglutinin polypeptide is the globular head domain of B/seal/Netherlands/1/99 HA (or a B/seal/Netherlands/1/99-like influenza virus).

**[00165]** In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide provided herein comprises (i) the stem domain of the hemagglutinin from an influenza virus of the H3 subtype and (ii) the globular head domain of the hemagglutinin from an influenza virus of the H4 subtype (sometimes referred to herein as a "cH4/3 chimeric influenza hemagglutinin polypeptide"). In a specific embodiment, the stem domain of a cH4/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/09 HA (or the stem domain of an A/Perth/16/09-like influenza virus HA). In another specific embodiment, the stem domain of a cH4/3 chimeric influenza hemagglutinin polypeptide is the stem domain of A/Perth/16/09 HA (or the stem domain of an A/Perth/16/09-like influenza virus HA) and the globular head domain of the cH4/3 chimeric influenza hemagglutinin polypeptide is the globular head domain of A/duck/Czech/56 (or the globular head domain of an A/duck/Czech/56-like influenza virus HA).

**[00166]** In certain embodiments, a chimeric influenza virus hemagglutinin polypeptide provided herein is monomeric. In certain embodiments, a chimeric influenza virus hemagglutinin polypeptide provided herein is multimeric. In certain embodiments, a chimeric influenza virus hemagglutinin polypeptide provided herein is trimeric.

**[00167]** In certain embodiments, a chimeric influenza virus hemagglutinin polypeptide provided herein comprises a signal peptide. Typically, the signal peptide is cleaved during or after polypeptide expression and translation to yield a mature chimeric influenza virus hemagglutinin polypeptide. In certain embodiments, also provided herein are mature chimeric influenza virus hemagglutinin polypeptides that lack a signal peptide. In embodiments where a chimeric influenza virus hemagglutinin polypeptide provided herein comprises a signal peptide, the signal peptide might be based on any influenza virus signal peptide known to those of skill in

the art. In certain embodiments, the signal peptides are based on influenza A signal peptides. In certain embodiments, the signal peptides are based on the signal peptide of an influenza A hemagglutinin selected from the group consisting of H1, H2, H3, H4, H5, H6, H7, H8, H9, H10, H11, H12, H13, H14, H15, H16, H17, and H18 (*See, e.g.*, Tong *et al.,* 2013. *PLoS Path.* 9(10): e1003657. Doi:10.1371/journal.ppat.1003657 for examples of an influenza A virus hemagglutinin H18). In certain embodiments, the signal peptide might be any signal peptide deemed useful to one of skill in the art.

**[00168]** In certain embodiments, a chimeric influenza virus hemagglutinin polypeptide provided herein comprises a luminal domain. In embodiments where a chimeric influenza virus hemagglutinin polypeptide provided herein comprises a luminal domain, the luminal domain might be based on any influenza luminal domain known to those of skill in the art. In certain embodiments, the luminal domains are based on influenza A luminal domains. In certain embodiments, the luminal domains are based on the luminal domain of an influenza A hemagglutinin selected from the group consisting of H1, H2, H3, H4, H5, H6, H7, H8, H9, H10, H11, H12, H13, H14, H15, H16, H17, and H18. In certain embodiments, the luminal domain might be any luminal domain deemed useful to one of skill in the art. In certain embodiments, the luminal domains are from the same hemagglutinin as the stem domain. In certain embodiments, the luminal domains are from influenza virus strain or subtype as the stem domain HA2 subunit.

**[00169]** In certain embodiments, a chimeric influenza virus hemagglutinin polypeptide provided herein comprises a transmembrane domain. In embodiments where a chimeric influenza virus hemagglutinin polypeptide provided herein comprises a transmembrane domain, the transmembrane domain might be based on any influenza transmembrane domain known to those of skill in the art. In certain embodiments, the transmembrane domains are based on influenza A transmembrane domains. In certain embodiments, the transmembrane domains are based on a transmembrane domain of an influenza A hemagglutinin selected from the group consisting of H1, H2, H3, H4, H5, H6, H7, H8, H9, H10, H11, H12, H13, H14, H15, H16, H17, and H18. In certain embodiments, the transmembrane domain might be any transmembrane domain deemed useful to one of skill in the art. In certain embodiments, the transmembrane domains are from the same hemagglutinin as the stem domain. In certain embodiments, the

transmembrane domains are from influenza virus strain or subtype as the stem domain HA2 subunit.

**[00170]** In certain embodiments, a chimeric influenza virus hemagglutinin polypeptide provided herein comprises a cytoplasmic domain. In embodiments where a chimeric influenza virus hemagglutinin polypeptide provided herein comprises a cytoplasmic domain, the cytoplasmic domain might be based on any influenza cytoplasmic domain known to those of skill in the art. In certain embodiments, the cytoplasmic domains are based on influenza A cytoplasmic domains. In certain embodiments, the cytoplasmic domains are based on a cytoplasmic domain of an influenza A hemagglutinin selected from the group consisting of H1, H2, H3, H4, H5, H6, H7, H8, H9, H10, H11, H12, H13, H14, H15, H16, H17, and H18. In certain embodiments, the cytoplasmic domain might be any cytoplasmic domain deemed useful to one of skill in the art. In certain embodiments, the cytoplasmic domains are from the same hemagglutinin as the stem domain. In certain embodiments, the cytoplasmic domains are from influenza virus strain or subtype as the stem domain HA2 subunit.

**[00171]** In certain embodiments, the chimeric influenza virus hemagglutinin polypeptides provided herein further comprise one or more polypeptide domains. Useful polypeptide domains include domains that facilitate purification, folding and cleavage of portions of a polypeptide. For example, a His tag (His-His-His-His-His-His, SEQ ID NO:17), FLAG epitope or other purification tag can facilitate purification of a chimeric influenza virus hemagglutinin polypeptide provided herein. In some embodiments, the His tag has the sequence, $(His)_n$, wherein n is 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20 or greater. A foldon, or trimerization, domain from bacteriophage T4 fibritin can facilitate trimerization of polypeptides provided herein. In some embodiments, the trimerization domain comprises a wildtype GCN4pII trimerization heptad repeat or a modified GCN4pII trimerization heptad repeat that allows for the formation of trimeric or tetrameric coiled coils. See,e.g., Weldon *et al.*, 2010, *PLoSONE* 5(9): e12466. The foldon domain can have any foldon sequence known to those of skill in the art (*see, e.g.,* Papanikolopoulou *et al.*, 2004, *J. Biol. Chem.* 279(10):8991-8998, the contents of which are hereby incorporated by reference in their entirety). Examples include GSGYIPEAPRDGQAYVRKDGEWVLLSTFL (SEQ ID NO:18). A foldon domain can be useful to facilitate trimerization of soluble polypeptides provided herein. Cleavage sites can be used to facilitate cleavage of a portion of a polypeptide, for example cleavage of a purification

tag or foldon domain or both. Useful cleavage sites include a thrombin cleavage site, for example one with the sequence LVPRGSP (SEQ ID NO:19). In certain embodiments, the cleavage site is a cleavage site recognized by Tobacco Etch Virus (TEV) protease (e.g., amino acid sequence Glu-Asn-Leu-Tyr-Phe-Gln-(Gly/Ser) (SEQ ID NO:20)).

**[00172]** In certain embodiments, the chimeric influenza hemagglutinin polypeptides described herein are soluble polypeptides.

**[00173]** In certain embodiments, the influenza hemagglutinin stem domain polypeptides of the chimeric influenza virus hemagglutinin polypeptides described herein maintain the cysteine residues identified in influenza hemagglutinin polypeptides as $A_p$ and $A_q$ in FIG. 1, i.e., the cysteine residues identified in influenza hemagglutinin polypeptides as $A_p$ and $A_q$ in FIG. 1 are maintained in the chimeric influenza virus hemagglutinin polypeptides described herein. Thus, in certain embodiments, in the primary sequence of a chimeric influenza virus hemagglutinin polypeptide described herein: (i) the N-terminal segment of an influenza hemagglutinin stem domain polypeptide ends at the cysteine residue identified as $A_p$ in FIG. 1, (ii) the C-terminal segment of an influenza hemagglutinin stem domain polypeptide begins at the cysteine residue identified as $A_q$ in FIG. 1; and (iii) the influenza hemagglutinin head domain polypeptide (which is heterologous to the influenza hemagglutinin stem domain polypeptide) is between the N-terminal and C-terminal segments of the influenza hemagglutinin stem domain polypeptide.

**[00174]** In certain embodiments, the HA1 N-terminal stem segment of the chimeric influenza virus hemagglutinin polypeptides described herein does not end exactly at $A_p$ (*e.g.*, $Cys_{52}$ of an HA1 subunit from an H3 hemagglutinin), but at a residue in sequence and structural vicinity to $A_p$. For example, in certain embodiments, the HA1 N-terminal stem segment of the chimeric influenza virus hemagglutinin polypeptides described herein ends at $A_{p-1}$, $A_{p-2}$, $A_{p-3}$, $A_{p-4}$, $A_{p-5}$, $A_{p-6}$, $A_{p-7}$, $A_{p-8}$, $A_{p-9}$, $A_{p-10}$. In certain embodiments, the HA1 N-terminal stem segment of the chimeric influenza virus hemagglutinin polypeptides described herein ends in the range of $A_{p-1}$ to $A_{p-3}$, $A_{p-3}$ to $A_{p-5}$, $A_{p-5}$ to $A_{p-8}$, $A_{p-8}$ to $A_{p-10}$. For example, an HA1 N-terminal stem segment ending at $A_{p-10}$ would end at Lys42 of an H3 hemagglutinin. In certain embodiments, the HA1 N-terminal stem segment of the chimeric influenza virus hemagglutinin polypeptides described herein ends at $A_{p+1}$, $A_{p+2}$, $A_{p+3}$, $A_{p+4}$, $A_{p+5}$, $A_{p+6}$, $A_{p+7}$, $A_{p+8}$, $A_{p+9}$, $A_{p+10}$. In certain embodiments, the HA1 N-terminal stem segment of the chimeric influenza virus hemagglutinin polypeptides

described herein ends in the range of $A_{p+1}$ to $A_{p+5}$, $A_{p+5}$ to $A_{p+10}$. The end of an HA1 N-terminal stem segment should be selected in conjunction with the end of the HA1 C-terminal stem segment and the influenza hemagglutinin head domain polypeptide so that the resulting chimeric influenza virus hemagglutinin polypeptide is capable of forming a three-dimensional structure similar to a wild-type influenza hemagglutinin. In such embodiments, an influenza hemagglutinin head domain polypeptide (which is heterologous to the influenza hemagglutinin stem domain polypeptide) is located, in primary sequence, between the N-terminal and C-terminal segments of the influenza hemagglutinin stem domain polypeptide.

**[00175]** In certain embodiments, the HA1 C-terminal stem segment of the chimeric influenza virus hemagglutinin polypeptides described herein does not start exactly at $A_q$ (*e.g.*, $Cys_{277}$ of an HA1 subunit from an H3 hemagglutinin), but at a residue in sequence and structural vicinity to $A_q$. For example, in certain embodiments, the HA1 C-terminal stem segment of the chimeric influenza virus hemagglutinin polypeptides described herein starts at about $A_{q-1}$, $A_{q-2}$, $A_{q-3}$, $A_{q-4}$, $A_{q-5}$, $A_{q-6}$, $A_{q-7}$, $A_{q-8}$, $A_{q-9}$, $A_{q-10}$. In certain embodiments, the HA1 C-terminal stem segment of the chimeric influenza virus hemagglutinin polypeptides described herein starts in the range of $A_{q-1}$ to $A_{q-5}$, $A_{q-5}$ to $A_{q-10}$. For example, an HA1 C-terminal stem segment ending at $A_{q-10}$ would start at Isoleucine262 of an H3 hemagglutinin. In certain embodiments, the HA1 C-terminal stem segment of the chimeric influenza virus hemagglutinin polypeptides described herein starts at $A_{q+1}$, $A_{q+2}$, $A_{q+3}$, $A_{q+4}$, $A_{q+5}$, $A_{q+6}$, $A_{q+7}$, $A_{q+8}$, $A_{q+9}$, $A_{q+10}$. In certain embodiments, the HA1 C-terminal stem segment of the chimeric influenza virus hemagglutinin polypeptides described herein starts in the range of $A_{q+1}$ to $A_{q+3}$, $A_{q+3}$ to $A_{q+5}$, $A_{q+5}$ to $A_{q+8}$, $A_{q+8}$ to $A_{q+10}$. The end of an HA1 N-terminal stem segment should be selected in conjunction with the start of the HA1 C-terminal stem segment and the influenza hemagglutinin head domain polypeptide so that the resulting chimeric influenza virus hemagglutinin polypeptide is capable of forming a three-dimensional structure similar to a wild-type influenza hemagglutinin. In such embodiments, an influenza hemagglutinin head domain polypeptide (which is heterologous to the influenza hemagglutinin stem domain polypeptide) is located, in primary sequence, between the N-terminal and C-terminal segments of the influenza hemagglutinin stem domain polypeptide.

**[00176]** In one example, an HA1 N-terminal stem segment of a chimeric influenza virus hemagglutinin polypeptide described herein may end at any one of hemagglutinin amino acid positions 45-48 (using H3 numbering) and an HA1 C-terminal stem segment of the chimeric

influenza virus hemagglutinin polypeptide may start at any one of hemagglutinin amino acid positions 282-287 (using H3 numbering); and the heterologous head domain may begin at any one of amino acid positions 46-49 and end at any one of amino acid position 284-289 (using H3 numbering).

**[00177]** In certain embodiments, when the stem domain of the chimeric influenza virus hemagglutinin polypeptides described herein is derived from an influenza B virus, the HA1 N-terminal stem segment may end at, e.g., amino acid 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, or 50 of the HA (in primary amino acid sequence), and the HA1 C-terminal stem segment may begin at, e.g., amino amino acid 280, 281, 282, 283, 284, 285, 286, 287, 288, 289, 290, 291, 292, 293, 294, 295, 296, 297, 298, 299, or 300 of the HA (in primary amino acid sequence). The globular head domain of the chimeric influenza virus hemagglutinin polypeptide thus would be inserted between the HA1 N-terminal stem segment and the HA1 C-terminal stem segment of the influenza B virus stem domain. For example, in the HA of influenza virus B/Hong Kong/8/73(PDB:2RFT: GenBank:M10298.1), the HA1 N-terminal stem segment would begin with amino acids DRICT (SEQ ID NO:22), with "D" being position 1, and would end at amino acid position 42 (in primary sequence); and the HA1 C-terminal stem segment would begin at amino acid position 288 (in primary sequence) and continue to the end of the C-terminus of the HA.

**[00178]** In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide described herein may be conjugated to heterologous proteins, e.g., a major histocompatibility complex (MHC) with or without heat shock proteins (e.g., Hsp10, Hsp20, Hsp30, Hsp40, Hsp60, Hsp70, Hsp90, or Hsp100). In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide described herein may be conjugated to immunomodulatory molecules, such as proteins which would target the chimeric influenza hemagglutinin (HA) polypeptide to immune cells such as B cells (e.g., C3d) or T cells. In certain embodiments, chimeric influenza hemagglutinin (HA) polypeptide described herein may be conjugated to proteins which stimulate the innate immune system such as interferon type 1, alpha, beta, or gamma interferon, colony stimulating factors such as granulocyte-macrophage colony-stimulating factor (GM-CSF), interleukin (IL)-1, IL-2, IL-4, IL-5, IL-6, IL-7, IL-12, IL-15, IL-18, IL-21, IL-23, tumor necrosis factor (TNF)-β, TNFα, B7.1, B7.2, 4-1BB, CD40 ligand (CD40L), and drug-inducible CD40 (iCD40).

**[00179]** It will be understood by those of skill in the art that the chimeric influenza virus hemagglutinin polypeptides provided herein can be prepared according to any technique known by and deemed suitable to those of skill in the art, including the techniques described herein. In certain embodiments, the chimeric influenza virus hemagglutinin polypeptides are isolated.

## 5.2 NUCLEIC ACIDS ENCODING CHIMERIC INFLUENZA VIRUS HEMAGGLUTININ (HA) POLYPEPTIDES

**[00180]** Provided herein are nucleic acids that encode the chimeric influenza hemagglutinin (HA) polypeptides described herein (e.g., the chimeric influenza hemagglutinin (HA) polypeptides described in Section 5.1). Due to the degeneracy of the genetic code, any nucleic acid that encodes a chimeric influenza hemagglutinin (HA) polypeptide described herein is encompassed herein. In certain embodiments, nucleic acids corresponding to, or capable of hybridizing with, naturally occurring influenza virus nucleic acids encoding an HA1 N-terminal stem segment, an HA1 C-terminal stem segment, HA2 domain, luminal domain, transmembrane domain, and/or cytoplasmic domain are used to produce a chimeric influenza hemagglutinin (HA) polypeptide described herein.

**[00181]** Also provided herein are nucleic acids capable of hybridizing to a nucleic acid encoding a chimeric influenza hemagglutinin (HA) polypeptide described herein (e.g., the chimeric influenza hemagglutinin (HA) polypeptides described in Section 5.1). In certain embodiments, provided herein are nucleic acids capable of hybridizing to a fragment of a nucleic acid encoding a chimeric influenza hemagglutinin (HA) polypeptide described herein. In other embodiments, provided herein are nucleic acids capable of hybridizing to the full length nucleic acid encoding a chimeric influenza hemagglutinin (HA) polypeptide described herein. General parameters for hybridization conditions for nucleic acids are described in Sambrook *et al.*, Molecular Cloning - A Laboratory Manual (2nd Ed.), Vols. 1-3, Cold Spring Harbor Laboratory, Cold Spring Harbor, New York (1989), and in Ausubel *et al.*, Current Protocols in Molecular Biology, vol. 2, Current Protocols Publishing, New York (1994). Hybridization may be performed under high stringency conditions, medium stringency conditions, or low stringency conditions. Those of skill in the art will understand that low, medium and high stringency conditions are contingent upon multiple factors all of which interact and are also dependent upon the nucleic acids in question. For example, high stringency conditions may include temperatures

within 5°C melting temperature of the nucleic acid(s), a low salt concentration (e.g., less than 250 mM), and a high co-solvent concentration (e.g., 1-20% of co-solvent, e.g., DMSO). Low stringency conditions, on the other hand, may include temperatures greater than 10°C below the melting temperature of the nucleic acid(s), a high salt concentration (e.g., greater than 1000 mM) and the absence of co-solvents.

**[00182]** In some embodiments, a nucleic acid encoding a chimeric influenza hemagglutinin (HA) polypeptide described herein is isolated. In certain embodiments, an "isolated" nucleic acid refers to a nucleic acid molecule which is separated from other nucleic acid molecules which are present in the natural source of the nucleic acid. In other words, the isolated nucleic acid can comprise heterologous nucleic acids that are not associated with it in nature. In other embodiments, an "isolated" nucleic acid, such as a cDNA molecule, can be substantially free of other cellular material, or culture medium when produced by recombinant techniques, or substantially free of chemical precursors or other chemicals when chemically synthesized. The term "substantially free of cellular material" includes preparations of nucleic acid in which the nucleic acid is separated from cellular components of the cells from which it is isolated or recombinantly produced. Thus, nucleic acid that is substantially free of cellular material includes preparations of nucleic acid having less than about 30%, 20%, 10%, or 5% (by dry weight) of other nucleic acids. The term "substantially free of culture medium" includes preparations of nucleic acid in which the culture medium represents less than about 50%, 20%, 10%, or 5% of the volume of the preparation. The term "substantially free of chemical precursors or other chemicals" includes preparations in which the nucleic acid is separated from chemical precursors or other chemicals which are involved in the synthesis of the nucleic acid. In specific embodiments, such preparations of the nucleic acid have less than about 50%, 30%, 20%, 10%, 5% (by dry weight) of chemical precursors or compounds other than the nucleic acid of interest.

**[00183]** In addition, provided herein are nucleic acids encoding the individual components of a chimeric influenza hemagglutinin (HA) polypeptide described herein, e.g., nucleic acids encoding the globular head domain, the HA1 N-terminal stem segment, the HA1 C-terminal stem segment and/or the HA2 domain a chimeric influenza hemagglutinin (HA) polypeptide described herein are provided herein. Nucleic acids encoding components of a chimeric influenza hemagglutinin (HA) polypeptide described herein may be assembled using standard

molecular biology techniques known to the one of skill in the art so as to yield a chimeric influenza hemagglutinin (HA) polypeptide described herein.

## 5.3 EXPRESSION OF CHIMERIC INFLUENZA VIRUS HEMAGGLUTININ (HA) POLYPEPTIDES

**[00184]** Provided herein are vectors, including expression vectors, containing a nucleic acid encoding a chimeric influenza hemagglutinin (HA) polypeptide described herein (e.g., the chimeric influenza hemagglutinin (HA) polypeptides described in Section 5.1). In a specific embodiment, the vector is an expression vector that is capable of directing the expression of a nucleic acid encoding a chimeric influenza hemagglutinin (HA) polypeptide described herein. Non-limiting examples of expression vectors include, but are not limited to, plasmids and viral vectors, such as replication defective retroviruses, adenoviruses, adeno-associated viruses and baculoviruses. Expression vectors also may include, without limitation, transgenic animals and non-mammalian cells/organisms, e.g., mammalian cells/organisms that have been engineered to perform mammalian N-linked glycosylation.

**[00185]** In some embodiments, provided herein are expression vectors encoding components of a chimeric influenza hemagglutinin (HA) polypeptide described herein. Such vectors may be used to express the components in one or more host cells and the components may be isolated and conjugated together with a linker using techniques known to one of skill in the art.

**[00186]** An expression vector comprises a nucleic acid encoding a chimeric influenza hemagglutinin (HA) polypeptide described herein in a form suitable for expression of the nucleic acid in a host cell. In a specific embodiment, an expression vector includes one or more regulatory sequences, selected on the basis of the host cells to be used for expression, which is operably linked to the nucleic acid to be expressed. Within an expression vector, "operably linked" is intended to mean that a nucleic acid of interest is linked to the regulatory sequence(s) in a manner which allows for expression of the nucleic acid (*e.g.*, in an *in vitro* transcription/translation system or in a host cell when the vector is introduced into the host cell). Regulatory sequences include promoters, enhancers and other expression control elements (*e.g.*, polyadenylation signals). Regulatory sequences include those which direct constitutive expression of a nucleic acid in many types of host cells, those which direct expression of the nucleic acid only in certain host cells (*e.g.*, tissue-specific regulatory sequences), and those

which direct the expression of the nucleic acid upon stimulation with a particular agent (*e.g.*, inducible regulatory sequences). It will be appreciated by those skilled in the art that the design of the expression vector can depend on such factors as the choice of the host cell to be transformed, the level of expression of protein desired, etc. The term "host cell" is intended to include a particular subject cell transformed or transfected with a nucleic acid and the progeny or potential progeny of such a cell. Progeny of such a cell may not be identical to the parent cell transformed or transfected with the nucleic acid due to mutations or environmental influences that may occur in succeeding generations or integration of the nucleic acid into the host cell genome.

**[00187]** Expression vectors can be designed for expression of a chimeric influenza hemagglutinin (HA) polypeptide described herein using prokaryotic (*e g.*, *E. coli*) or eukaryotic cells (*e.g.*, insect cells (using baculovirus expression vectors, see, e.g., Treanor et al., 2007, JAMA, 297(14):1577-1582 incorporated by reference herein in its entirety), yeast cells, plant cells, algae or mammalian cells). Examples of yeast host cells include, but are not limited to *S. pombe, S. cerevisiae,* and *P. pastoris* and examples, infra. Examples of mammalian host cells include, but are not limited to, Crucell Per.C6 cells, Vero cells, CHO cells, VERY cells, BHK cells, HeLa cells, COS cells, MDCK cells, 293 cells, 3T3 cells or WI38 cells. In certain embodiments, the hosts cells are myeloma cells, *e.g.*, NS0 cells, 45.6 TG1.7 cells, AF-2 clone 9B5 cells, AF-2 clone 9B5 cells, J558L cells, MOPC 315 cells, MPC-11 cells, NCI-H929 cells, NP cells, NS0/1 cells, P3 NS1 Ag4 cells, P3/NS1/1-Ag4-1 cells, P3U1 cells, P3X63Ag8 cells, P3X63Ag8.653 cells, P3X63Ag8U.1 cells, RPMI 8226 cells, Sp20-Ag14 cells, U266B1 cells, X63AG8.653 cells, Y3.Ag.1.2.3 cells, and YO cells. Non-limiting examples of insect cells include *Sf*9, *Sf*21, Ao/Tn 38, High Five, *Trichoplusia ni*, *Spodoptera frugiperda* and *Bombyx mori*. In a particular embodiment, a mammalian cell culture system (e.g. Chinese hamster ovary or baby hamster kidney cells) is used for expression of a chimeric influenza hemagglutinin (HA) polypeptide. In another embodiment, a plant cell culture sytem is used for expression of a chimeric influenza hemagglutinin (HA) polypeptide. See, *e.g.*, U.S. Patent Nos. 7,504,560; 6,770,799; 6,551,820; 6,136,320; 6,034,298; 5,914,935; 5,612,487; and 5,484,719, and U.S. patent application publication Nos. 2009/0208477, 2009/0082548, 2009/0053762, 2008/0038232, 2007/0275014 and 2006/0204487 for plant cells and methods for the production of proteins utilizing plant cell culture systems. In specific embodiments, plant cell culture

systems are not used for expression of a chimeric influenza hemagglutinin (HA) polypeptide described herein.

**[00188]** In certain embodiments, plants (e.g., plants of the genus *Nicotiana*) may be engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described in Section 5.1). In specific embodiments, plants are engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein via an agroinfiltration procedure using methods known in the art. For example, nucleic acids encoding a gene of interest, e.g., a gene encoding a chimeric influenza hemagglutinin (HA) polypeptide described herein, is introduced into a strain of Agrobacterium. Subsequently the strain is grown in a liquid culture and the resulting bacteria are washed and suspended into a buffer solution. The plants are then exposed (e.g., via injection or submersion) to the Agrobacterium that comprises the nucleic acids encoding a fl chimeric influenza hemagglutinin (HA) polypeptide described herein such that the Agrobacterium transforms the gene of interest to a portion of the plant cells. The chimeric influenza hemagglutinin (HA) polypeptide is then transiently expressed by the plant and can isolated using methods known in the art and described herein. (For specific examples see Shoji et al., 2008, Vaccine, 26(23):2930-2934; and D'Aoust et al., 2008, J. Plant Biotechnology, 6(9):930-940). In a specific embodiment, the plant is a tobacco plant (e.g., *Nicotiana tabacum*). In another specific embodiment, the plant is a relative of the tobacco plant (e.g., *Nicotiana benthamiana*). In another specific embodiment, the chimeric influenza hemagglutinin (HA) polypeptides described herein are expressed in a species of soy. In another specific embodiment, the chimeric influenza hemagglutinin (HA) polypeptides described herein are expressed in a species of corn. In another specific embodiment, the chimeric influenza hemagglutinin (HA) polypeptides described herein are expressed in a species of rice.

**[00189]** In other embodiments, algae (e.g., *Chlamydomonas reinhardtii*) may be engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein, e.g., a chimeric influenza hemagglutinin (HA) polypeptide described in Section 5.1 (see, e.g., Rasala et al., 2010, Plant Biotechnology Journal (Published online March 7, 2010)).

**[00190]** In certain embodiments, the plants used to express the chimeric influenza hemagglutinin (HA) polypeptides described herein are engineered to express components of an

N-glycosylation system (e.g., a bacterial or mammalian N-glycosylation system), i.e., the plants can perform N-glycosylation.

**[00191]** Plant cells that can be used to express the chimeric influenza hemagglutinin (HA) polypeptides described herein and methods for the production of proteins utilizing plant cell culture systems are described in, e.g., U.S. Patent Nos. 5,929,304; 7,504,560; 6,770,799; 6,551,820; 6,136,320; 6,034,298; 5,914,935; 5,612,487; and 5,484,719, U.S. patent application publication Nos. 2009/0208477, 2009/0082548, 2009/0053762, 2008/0038232, 2007/0275014 and 2006/0204487, and Shoji et al., 2008, Vaccine, 26(23):2930-2934, and D'Aoust et al., 2008, J. Plant Biotechnology, 6(9):930-940 (which are incorporated herein by reference in their entirety).

**[00192]** The host cells comprising the nucleic acids that encode the chimeric influenza hemagglutinin (HA) polypeptide described herein can be isolated, e.g., the cells are outside of the body of a subject or are isolated (i.e., separated from) untransfected/untransformed host cells. In certain embodiments, the cells are engineered to express nucleic acids that encode the chimeric influenza hemagglutinin (HA) polypeptides described herein.

**[00193]** An expression vector can be introduced into host cells via conventional transformation or transfection techniques. Such techniques include, but are not limited to, calcium phosphate or calcium chloride co-precipitation, DEAE-dextran-mediated transfection, lipofection, and electroporation. Suitable methods for transforming or transfecting host cells can be found in Sambrook *et al.*, 1989, Molecular Cloning - A Laboratory Manual, 2nd Edition, Cold Spring Harbor Press, New York, and other laboratory manuals. In certain embodiments, a host cell is transiently transfected with an expression vector containing a nucleic acid encoding chimeric influenza hemagglutinin (HA) polypeptide. In other embodiments, a host cell is stably transfected with an expression vector containing a nucleic acid encoding a chimeric influenza hemagglutinin (HA) polypeptide.

**[00194]** For stable transfection of mammalian cells, it is known that, depending upon the expression vector and transfection technique used, only a small fraction of cells may integrate the foreign DNA into their genome. In order to identify and select these integrants, a nucleic acid that encodes a selectable marker (*e.g.*, for resistance to antibiotics) is generally introduced into the host cells along with the nucleic acid of interest. Examples of selectable markers include those which confer resistance to drugs, such as G418, hygromycin and methotrexate. Cells

stably transfected with the introduced nucleic acid can be identified by drug selection (*e.g.*, cells that have incorporated the selectable marker gene will survive, while the other cells die).

**[00195]** As an alternative to recombinant expression of a chimeric influenza hemagglutinin (HA) polypeptide described herein using a host cell, an expression vector containing a nucleic acid encoding a chimeric influenza hemagglutinin (HA) polypeptide can be transcribed and translated *in vitro* using, *e.g.*, T7 promoter regulatory sequences and T7 polymerase. In a specific embodiment, a coupled transcription/translation system, such as Promega TNT®, or a cell lysate or cell extract comprising the components necessary for transcription and translation may be used to produce a chimeric influenza hemagglutinin (HA) polypeptide described herein.

**[00196]** Once a chimeric influenza hemagglutinin (HA) polypeptide described herein has been produced, it may be isolated or purified by any method known in the art for isolation or purification of a protein, for example, by chromatography (*e.g.*, ion exchange, affinity, particularly by affinity for the specific antigen or a "tag" associated with the antigen (e.g., a HIS tag , strep tag/strep II tag, a maltose binding protein, a glutatione S-transferase tag, myc tag, HA tag), by Protein A, and chromatography (e.g., sizing column chromatography, hydrophopic interaction chromatography (HIC), reversed phase chromatography, simulated moving bed chromatography, size eclusion chromatography, monolith chromatography, convective interaction media chromatography, lectin chromatography)), centrifugation, differential solubility, ultrafiltration, precipitation, or by any other standard technique for the isolation or purification of proteins. In specific embodiments, the isolated/purified chimeric influenza hemagglutinin (HA) polypeptides described herein are soluble, e.g., made soluble using any method known to those of skill in the art, e.g., the methods described herein (see, e.g., Section 6.6.1.2).

**[00197]** Provided herein are methods for producing a chimeric influenza hemagglutinin (HA) polypeptide described herein. In one embodiment, the method comprises culturing a host cell containing a nucleic acid encoding the polypeptide in a suitable medium such that the polypeptide is produced. In some embodiments, the method further comprises isolating the polypeptide from the medium or the host cell.

## 5.4 INFLUENZA VIRUS VECTORS

**[00198]** In one aspect, provided herein are influenza viruses containing a chimeric influenza hemagglutinin (HA) polypeptide described herein (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described in Section 5.1). In a specific embodiment, the chimeric influenza hemagglutinin (HA) polypeptide described herein is incorporated into the virions of the influenza virus. The influenza viruses may be conjugated to moieties that target the viruses to particular cell types, such as immune cells. In some embodiments, the virions of the influenza virus have incorporated into them or express a heterologous polypeptide in addition to a chimeric influenza hemagglutinin (HA) polypeptide described herein. The heterologous polypeptide may be a polypeptide that has immunopotentiating activity, or that targets the influenza virus to a particular cell type, such as an antibody that binds to an antigen on a specific cell type or a ligand that binds a specific receptor on a specific cell type.

**[00199]** Influenza viruses containing a chimeric influenza hemagglutinin (HA) polypeptide described herein may be produced by supplying in *trans* the chimeric influenza hemagglutinin (HA) polypeptide during production of virions using techniques known to one skilled in the art, such as reverse genetics and helper-free plasmid rescue. Alternatively, the replication of a parental influenza virus comprising a genome engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein in cells susceptible to infection with the virus wherein hemagglutinin function is provided in *trans* will produce progeny influenza viruses containing the chimeric influenza hemagglutinin (HA) polypeptide.

**[00200]** In another aspect, provided herein are influenza viruses comprising a genome engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described in Section 5.1). In a specific embodiment, the genome of a parental influenza virus is engineered to encode a chimeric influenza hemagglutinin (HA) polypeptide described herein, which is expressed by progeny influenza virus. In another specific embodiment, the genome of a parental influenza virus is engineered to encode a chimeric influenza hemagglutinin (HA) polypeptide described herein, which is expressed and incorporated into the virions of progeny influenza virus. Thus, the progeny influenza virus resulting from the replication of the parental influenza virus contain a chimeric influenza hemagglutinin (HA) polypeptide described herein. The virions of the parental influenza virus may have incorporated into them a chimeric influenza hemagglutinin (HA) polypeptide that contains a stem or head domain from the same or a different type, subtype

or strain of influenza virus. Alternatively, the virions of the parental influenza virus may have incorporated into them a moiety that is capable of functionally replacing one or more of the activities of influenza virus hemagglutinin polypeptide (*e.g.*, the receptor binding and/or fusogenic activities of influenza virus hemagglutinin). In certain embodiments, one or more of the activities of the influenza virus hemagglutinin polypeptide is provided by a fusion protein comprising (i) an ectodomain of a polypeptide heterologous to influenza virus fused to (ii) a transmembrane domain, or a transmembrane domain and a cytoplasmic domain of an influenza virus hemagglutinin polypeptide. In a specific embodiment, the virions of the parental influenza virus may have incorporated into them a fusion protein comprising (i) an ectodomain of a receptor binding/fusogenic polypeptide of an infectious agent other than influenza virus fused to (ii) a transmembrane domain, or a transmembrane domain and a cytoplasmic domain of an influenza virus hemagglutinin. For a description of fusion proteins that provide one or more activities of an influenza virus hemagglutinin polypeptide and methods for the production of influenza viruses engineered to express such fusion proteins, see, *e.g.*, International patent application Publication No. WO 2007/064802, published June 7, 2007 and U.S. patent application publication no. 2012/0122185; each of which is incorporated herein by reference in its entirety.

**[00201]** In certain embodiments, the influenza viruses engineered to express one or more of the chimeric influenza hemagglutinin (HA) polypeptides described herein comprise a neuraminidase (NA), or fragment thereof, that is from the same source (e.g., influenza virus strain or subtype) as that from which the globular head domain of the chimeric influenza hemagglutinin (HA) polypeptide is derived. In certain embodiments, the influenza viruses engineered to express one or more of the chimeric influenza hemagglutinin polypeptides described herein comprise a neuraminidase (NA), or fragment thereof, that is from the same source (e.g., influenza virus strain or subtype) as that from which the globular head domain of the chimeric influenza hemagglutinin polypeptide is derived, wherein the globular head domain is heterologous to the stem domain of the HA1 and/or HA2 subunits of the chimeric influenza hemagglutinin polypeptide. In certain embodiments, the influenza viruses engineered to express one or more of the chimeric influenza hemagglutinin polypeptides described herein comprise a neuraminidase (NA), or fragment thereof, that is from the same source (e.g., influenza virus

strain or subtype) as that from which the HA stem domain of the chimeric influenza hemagglutinin polypeptide is derived.

**[00202]** In some embodiments, the virions of the parental influenza virus have incorporated into them a heterologous polypeptide. In certain embodiments, the genome of a parental influenza virus is engineered to encode a heterologous polypeptide and a chimeric influenza hemagglutinin (HA) polypeptide, which are expressed by progeny influenza virus. In specific embodiments, the chimeric influenza hemagglutinin (HA) polypeptide, the heterologous polypeptide, or both are incorporated into virions of the progeny influenza virus.

**[00203]** The heterologous polypeptide may be a polypeptide that targets the influenza virus to a particular cell type, such as an antibody that recognizes an antigen on a specific cell type or a ligand that binds a specific receptor on a specific cell type. In some embodiments, the targeting polypeptide replaces the target cell recognition function of the virus. In a specific embodiment, the heterologous polypeptide targets the influenza virus to the same cell types that influenza virus infects in nature. In other specific embodiments, the heterologous polypeptide targets the progeny influenza virus to immune cells, such as B cells, T cells, macrophages or dendritic cells. In some embodiments, the heterologous polypeptide recognizes and binds to cell-specific markers of antigen presenting cells, such as dendritic cells (*e.g.*, such as CD44). In one embodiment, the heterologous polypeptide is DC-SIGN which targets the virus to dendritic cells. In another embodiment, the heterologous polypeptide is an antibody (*e.g.*, a single-chain antibody) that targets the virus to an immune cell, which may be fused with a transmembrane domain from another polypeptide so that it is incorporated into the influenza virus virion. In some embodiments, the antibody is a CD20 antibody, a CD34 antibody, or an antibody against DEC-205. Techniques for engineering viruses to express polypeptides with targeting functions are known in the art. See, *e.g.*, Yang *et al.*, 2006, PNAS 103: 11479-11484 and United States patent application Publication No. 20080019998, published January 24, 2008, and No. 20070020238, published January 25, 2007, the contents of each of which are incorporated herein in their entirety.

**[00204]** In another embodiment, the heterologous polypeptide is a viral attachment protein. Non-limiting examples of viruses whose attachment protein(s) can be used in this aspect are viruses selected from the group of: Lassa fever virus, Hepatitis B virus, Rabies virus, Newcastle disease virus (NDV), a retrovirus such as human immunodeficiency virus, tick-borne

encephalitis virus, vaccinia virus, herpesvirus, poliovirus, alphaviruses such as Semliki Forest virus, Ross River virus, and Aura virus (which comprise surface glycoproteins such as E1, E2, and E3), Borna disease virus, Hantaan virus, foamyvirus, and SARS-CoV virus.

**[00205]** In one embodiment, a flavivirus surface glycoprotein may be used, such as Dengue virus (DV) E protein. In some embodiments, a Sindbis virus glycoprotein from the alphavirus family is used (K. S. Wang, R. J. Kuhn, E. G. Strauss, S. Ou, J. H. Strauss, J. Virol. 66, 4992 (1992)). In certain embodiments, the heterologous polypeptide is derived from an NDV HN or F protein; a human immunodeficiency virus (HIV) gp160 (or a product thereof, such as gp41 or gp120); a hepatitis B virus surface antigen (HBsAg); a glycoprotein of herpesvirus (e.g., gD, gE); or VP1 of poliovirus.

**[00206]** In another embodiment, the heterologous polypeptide is derived from any non-viral targeting system known in the art. In certain embodiments, a protein of a nonviral pathogen such as an intracellular bacteria or protozoa is used. In some embodiments, the bacterial polypeptide is provided by, *e.g.*, Chlamydia, Rikettsia, Coxelia, Listeria, Brucella, or Legionella. In some embodiments, protozoan polypeptide is provided by, *e.g.*, Plasmodia species, *Leishmania spp.*, *Toxoplasma gondii*, or *Trypanosoma cruzi*. Other exemplary targeting systems are described in Waehler *et al.*, 2007, "Engineering targeted viral vectors for gene therapy," Nature Reviews Genetics 8: 573-587, which is incorporated herein in its entirety.

**[00207]** In certain embodiments, the heterologous polypeptide expressed by an influenza virus has immunopotentiating (immune stimulating) activity. Non-limiting examples of immunopotentiating polypeptides include, but are not limited to, stimulation molecules, cytokines, chemokines, antibodies and other agents such as Flt-3 ligands. Specific examples of polypeptides with immunopotentiating activity include: interferon type 1, alpha, beta, or gamma interferon, colony stimulating factors such as granulocyte-macrophage colony-stimulating factor (GM-CSF), interleukin (IL)-1, IL-2, IL-4, IL-5, IL-6, IL-7, IL-12, IL-15, IL-18, IL-21, IL-23, tumor necrosis factor (TNF)-β, TNFα., B7.1, B7.2, 4-1BB, CD40 ligand (CD40L), and drug-inducible CD40 (iCD40) (see, *e.g.*, Hanks, B. A., *et al.* 2005. Nat Med 11:130-137, which is incorporated herein by reference in its entirety.)

**[00208]** Since the genome of influenza A and B viruses consist of eight (8) single-stranded, negative sense segments (influenza C viruses consist of seven (7) single-stranded, negative sense segments), the genome of a parental influenza virus may be engineered to express a chimeric

influenza hemagglutinin (HA) polypeptide described herein (and any other polypeptide, such as a heterologous polypeptide) using a recombinant segment and techniques known to one skilled in the art, such a reverse genetics and helper-free plasmid rescue. In one embodiment, the recombinant segment comprises a nucleic acid encoding the chimeric influenza hemagglutinin (HA) polypeptide as well as the 3' and 5' incorporation signals which are required for proper replication, transcription and packaging of the vRNAs (Fujii *et al.*, 2003, Proc. Natl. Acad. Sci. USA 100:2002-2007; Zheng, *et al.*, 1996, Virology 217:242-251, both of which are incorporated by reference herein in their entireties). In a specific embodiment, the recombinant segment uses the 3' and 5' noncoding and/or nontranslated sequences of segments of influenza viruses that are from a different or the same type, subtype or strain as the parental influenza virus. In some embodiments, the recombinant segment comprises the 3' noncoding region of an influenza virus hemagglutinin polypeptide, the untranslated regions of an influenza virus hemagglutinin polypeptide, and the 5' non-coding region of an influenza virus hemagglutinin polypeptide. In specific embodiments, the recombinant segment comprises the 3' and 5' noncoding and/or nontranslated sequences of the HA segment of an influenza virus that is the same type, subtype or strain as the influenza virus type, subtype or strain as the HA1 N-terminal stem segment, the HA1 C-terminal stem segment, the globular head domain, and/or the HA2 of a chimeric influenza hemagglutinin (HA) polypeptide. In certain embodiments, the recombinant segment encoding the chimeric influenza hemagglutinin (HA) polypeptide may replace the HA segment of a parental influenza virus. In some embodiments, the recombinant segment encoding the chimeric influenza hemagglutinin (HA) polypeptide may replace the NS1 gene of the parental influenza virus. In some embodiments, the recombinant segment encoding the chimeric influenza hemagglutinin (HA) polypeptide may replace the NA gene of the parental influenza virus. Exemplary influenza virus strains that can be used to express the chimeric influenza hemagglutinin (HA) polypeptides described herein include Ann Arbor/1/50, A/Ann Arbor/6/60, A/Puerto Rico/8/34, A/South Dakota/6/2007, A/Uruguay/716/2007, A/California/07/2009, A/Perth/16/2009, A/Brisbane/59/2007, A/Brisbane/10/2007, A/Leningrad/134/47/57, B/Brisbane/60/2008, B/Yamagata/1/88, A/Panama/2007/99, A/Wyoming/3/03, and A/WSN/33.

**[00209]** In some embodiments, an influenza virus hemagglutinin gene segment encodes a chimeric influenza hemagglutinin (HA) polypeptide described herein. In specific embodiments, the influenza virus hemagglutinin gene segment and at least one other influenza virus gene

segment comprise packaging signals that enable the influenza virus hemagglutinin gene segment and the at least one other gene segment to segregate together during replication of a recombinant influenza virus (see, Gao & Palese 2009, PNAS 106:15891-15896; International Application Publication No. WO11/014645; and U.S. Patent Application Publication No. 2012/0244183).

**[00210]** In some embodiments, the genome of a parental influenza virus may be engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein using a recombinant segment that is bicistronic. Bicistronic techniques allow the engineering of coding sequences of multiple proteins into a single mRNA through the use of internal ribosome entry site (IRES) sequences. IRES sequences direct the internal recruitment of ribosomes to the RNA molecule and allow downstream translation in a cap independent manner. Briefly, a coding region of one protein is inserted into the open reading frame (ORF) of a second protein. The insertion is flanked by an IRES and any untranslated signal sequences necessary for proper expression and/or function. The insertion must not disrupt the ORF, polyadenylation or transcriptional promoters of the second protein (see, *e.g.*, García-Sastre *et al.*, 1994, J. Virol. 68:6254-6261 and García-Sastre *et al.*, 1994 Dev. Biol. Stand. 82:237-246, each of which is hereby incorporated by reference in its entirety). *See* also, *e.g.*, U.S. Patent No. 6,887,699, U.S. Patent No. 6,001,634, U.S. Patent No. 5,854,037 and U.S. Patent No. 5,820,871, each of which is incorporated herein by reference in its entirety. Any IRES known in the art or described herein may be used in accordance with the invention (e.g., the IRES of BiP gene, nucleotides 372 to 592 of GenBank database entry HUMGRP78; or the IRES of encephalomyocarditis virus (EMCV), nucleotides 1430-2115 of GenBank database entry CQ867238.). Thus, in certain embodiments, a parental influenza virus is engineered to contain a bicistronic RNA segment that expresses the chimeric influenza hemagglutinin (HA) polypeptide and another polypeptide, such as a gene expressed by the parental influenza virus. In some embodiments, the parental influenza virus gene is the HA gene. In some embodiments, the parental influenza virus gene is the NA gene. In some embodiments, the parental influenza virus gene is the NS1 gene.

**[00211]** Techniques known to one skilled in the art may be used to produce an influenza virus containing a chimeric influenza hemagglutinin (HA) polypeptide described herein and an influenza virus comprising a genome engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein. For example, reverse genetics techniques may be used to generate such an influenza virus. Briefly, reverse genetics techniques generally involve the

preparation of synthetic recombinant viral RNAs that contain the non-coding regions of the negative-strand, viral RNA which are essential for the recognition by viral polymerases and for packaging signals necessary to generate a mature virion. The recombinant RNAs are synthesized from a recombinant DNA template and reconstituted *in vitro* with purified viral polymerase complex to form recombinant ribonucleoproteins (RNPs) which can be used to transfect cells. A more efficient transfection is achieved if the viral polymerase proteins are present during transcription of the synthetic RNAs either *in vitro* or *in vivo*. The synthetic recombinant RNPs can be rescued into infectious virus particles. The foregoing techniques are described in U.S. Patent No. 5,166,057 issued November 24, 1992; in U.S. Patent No. 5,854,037 issued December 29, 1998; in European Patent Publication EP 0702085A1, published February 20, 1996; in U.S. Patent Application Serial No. 09/152,845; in International Patent Publications PCT WO 97/12032 published April 3, 1997; WO 96/34625 published November 7, 1996; in European Patent Publication EP A780475; WO 99/02657 published January 21, 1999; WO 98/53078 published November 26, 1998; WO 98/02530 published January 22, 1998; WO 99/15672 published April 1, 1999; WO 98/13501 published April 2, 1998; WO 97/06270 published February 20, 1997; and EPO 780 475A1 published June 25, 1997, each of which is incorporated by reference herein in its entirety.

**[00212]** Alternatively, helper-free plasmid technology may be used to produce an influenza virus containing chimeric influenza hemagglutinin (HA) polypeptide described herein and an influenza virus comprising a genome engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein. Briefly, full length cDNAs of viral segments are amplified using PCR with primers that include unique restriction sites, which allow the insertion of the PCR product into the plasmid vector (Flandorfer *et al.*, 2003, J. Virol. 77:9116-9123; Nakaya *et al.*, 2001, J. Virol. 75:11868-11873; both of which are incorporated herein by reference in their entireties). The plasmid vector is designed so that an exact negative (vRNA sense) transcript is expressed. For example, the plasmid vector may be designed to position the PCR product between a truncated human RNA polymerase I promoter and a hepatitis delta virus ribozyme sequence such that an exact negative (vRNA sense) transcript is produced from the polymerase I promoter. Separate plasmid vectors comprising each viral segment as well as expression vectors comprising necessary viral proteins may be transfected into cells leading to production of recombinant viral particles. In another example, plasmid vectors from which both the viral

genomic RNA and mRNA encoding the necessary viral proteins are expressed may be used. For a detailed description of helper-free plasmid technology see, *e.g.*, International Publication No. WO 01/04333; U.S. Patent Nos. 6,951,754, 7,384,774, 6,649,372, and 7,312,064; Fodor *et al.*, 1999, J. Virol. 73:9679-9682; Quinlivan *et al.*, 2005, J. Virol. 79:8431-8439; Hoffmann *et al.*, 2000, Proc. Natl. Acad. Sci. USA 97:6108-6113; Neumann *et al.*, 1999, Proc. Natl. Acad. Sci. USA 96:9345-9350; Enami and Enami, 2000, J. Virol. 74(12):5556-5561; and Pleschka et al., 1996, J. Virol. 70(6):4188-4192, which are incorporated herein by reference in their entireties.

**[00213]** The influenza viruses described herein may be propagated in any substrate that allows the virus to grow to titers that permit their use in accordance with the methods described herein. In one embodiment, the substrate allows the viruses to grow to titers comparable to those determined for the corresponding wild-type viruses. In certain embodiments, the substrate is one which is biologically relevant to the influenza virus or to the virus from which the HA function is derived. In a specific embodiment, an attenuated influenza virus by virtue of, *e.g.*, a mutation in the NS1 gene, may be propagated in an IFN-deficient substrate. For example, a suitable IFN-deficient substrate may be one that is defective in its ability to produce or respond to interferon, or is one which an IFN-deficient substrate may be used for the growth of any number of viruses which may require interferon-deficient growth environment. See, for example, U.S. Patent Nos. 6,573,079, issued June 3, 2003, 6,852,522, issued February 8, 2005, and 7,494,808, issued February 24, 2009, the entire contents of each of which is incorporated herein by reference in its entirety. In a specific embodiment, the virus is propagated in embryonated eggs (e.g., chicken eggs). In a specific embodiment, the virus is propagated in 8 day old, 9-day old, 8-10 day old, 10 day old, 11-day old, 10-12 day old, or 12-day old embryonated eggs (e.g., chicken eggs). In certain embodiments, the virus is propagated in MDCK cells, Vero cells, 293T cells, or other cell lines known in the art. In certain embodiments, the virus is propagated in cells derived from embryonated eggs.

**[00214]** The influenza viruses described herein may be isolated and purified by any method known to those of skill in the art. In one embodiment, the virus is removed from cell culture and separated from cellular components, typically by well known clarification procedures, *e.g.*, such as gradient centrifugation and column chromatography, and may be further purified as desired using procedures well known to those skilled in the art, *e.g.*, plaque assays.

**[00215]** In certain embodiments, the influenza viruses, or influenza virus polypeptides, genes or genome segments for use as described herein are obtained or derived from an influenza A virus. In certain embodiments, the influenza viruses, or influenza virus polypeptides, genes or genome segments for use as described herein are obtained or derived from two or more influenza A virus subtypes or strains.

**[00216]** In some embodiments, the influenza viruses, or influenza virus polypeptides, genes or genome segments for use as described herein are obtained or derived from an influenza B virus. In certain embodiments, the influenza viruses, or influenza virus polypeptides, genes or genome segments for use as described herein are obtained or derived from two or more influenza B virus subtypes or strains. In other embodiments, the influenza viruses, or influenza virus polypeptides, genes or genome segments for use as described herein are obtained or derived from a combination of influenza A and influenza B virus subtypes or strains.

**[00217]** In some embodiments, the influenza viruses, or influenza virus polypeptides, genes or genome segments for use as described herein are obtained or derived from an influenza C virus. In certain embodiments, the influenza viruses, or influenza virus polypeptides, genes or genome segments for use as described herein are obtained or derived from two or more influenza C virus subtypes or strains. In other embodiments, the influenza viruses, or influenza virus polypeptides, genes or genome segments for use as described herein are obtained or derived from a combination of influenza C virus and influenza A virus and/or influenza B virus subtypes or strains.

**[00218]** In certain embodiments, the influenza viruses provided herein have an attenuated phenotype. In specific embodiments, the attenuated influenza virus is based on influenza A virus. In other embodiments, the attenuated influenza virus is based on influenza B virus. In yet other embodiments, the attenuated influenza virus is based on influenza C virus. In other embodiments, the attenuated influenza virus may comprise genes or genome segments from one or more strains or subtypes of influenza A, influenza B, and/or influenza C virus. In some embodiments, the attenuated backbone virus comprises genes from an influenza A virus and an influenza B virus.

**[00219]** In specific embodiments, attenuation of influenza virus is desired such that the virus remains, at least partially, infectious and can replicate *in vivo*, but only generate low titers resulting in subclinical levels of infection that are non-pathogenic. Such attenuated viruses are

especially suited for embodiments described herein wherein the virus or an immunogenic composition thereof is administered to a subject to induce an immune response. Attenuation of the influenza virus can be accomplished according to any method known in the art, such as, *e.g.*, selecting viral mutants generated by chemical mutagenesis, mutation of the genome by genetic engineering, selecting reassortant viruses that contain segments with attenuated function, or selecting for conditional virus mutants (*e.g.*, cold-adapted viruses). Alternatively, naturally occurring attenuated influenza viruses may be used as influenza virus backbones for the influenza virus vectors.

**[00220]** In one embodiment, an influenza virus may be attenuated, at least in part, by virtue of substituting the HA gene of the parental influenza virus with a chimeric influenza hemagglutinin (HA) polypeptide described herein. In some embodiments, an influenza virus may be attenuated, at least in part, by engineering the influenza virus to express a mutated NS1 gene that impairs the ability of the virus to antagonize the cellular interferon (IFN) response. Examples of the types of mutations that can be introduced into the influenza virus NS1 gene include deletions, substitutions, insertions and combinations thereof. One or more mutations can be introduced anywhere throughout the NS1 gene (*e.g.*, the N-terminus, the C-terminus or somewhere in between) and/or the regulatory element of the NS1 gene. In one embodiment, an attenuated influenza virus comprises a genome having a mutation in an influenza virus NS1 gene resulting in a deletion consisting of 5, preferably 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 75, 80, 85, 90, 95, 99, 100, 105, 110, 115, 120, 125, 126, 130, 135, 140, 145, 150, 155, 160, 165, 170 or 175 amino acid residues from the C-terminus of NS1, or a deletion of between 5-170, 25-170, 50-170, 100-170, 100-160, or 105-160 amino acid residues from the C-terminus. In another embodiment, an attenuated influenza virus comprises a genome having a mutation in an influenza virus NS1 gene such that it encodes an NS1 protein of amino acid residues 1-130, amino acid residues 1-126, amino acid residues 1-120, amino acid residues 1-115, amino acid residues 1-110, amino acid residues 1-100, amino acid residues 1-99, amino acid residues 1-95, amino acid residues 1-85, amino acid residues 1-83, amino acid residues 1-80, amino acid residues 1-75, amino acid residues 1-73, amino acid residues 1-70, amino acid residues 1-65, or amino acid residues 1-60, wherein the N-terminus amino acid is number 1. For examples of NS1 mutations and influenza viruses comprising a mutated NS1, see, *e.g.*, U.S. Patent Nos. 6,468,544

and 6,669,943; and Li *et al.*, 1999, J. Infect. Dis. 179:1132-1138, each of which is incorporated by reference herein in its entirety.

**[00221]** In another embodiment, an influenza virus may be attenuated, at least in part, by mutating an NA or M gene of the virus as described in the literature.

## 5.5 NON-INFLUENZA VIRUS VECTORS

**[00222]** In one aspect, provided herein are non-influenza viruses containing a chimeric influenza hemagglutinin (HA) polypeptide described herein (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described in Section 5.1). In a specific embodiment, the chimeric influenza hemagglutinin (HA) polypeptide described herein is incorporated into the virions of the non-influenza virus. In a specific embodiment, the chimeric influenza hemagglutinin (HA) polypeptide described herein is contained in/expressed by a purified (e.g., plaque purified) or isolated virus. The non-influenza viruses may be conjugated to moieties that target the viruses to particular cell types, such as immune cells. In some embodiments, the virions of the non-influenza virus have incorporated into them or express a heterologous polypeptide in addition to a chimeric influenza hemagglutinin (HA) polypeptide described herein. The heterologous polypeptide may be a polypeptide that has immunopotentiating activity, or that targets the non-influenza virus to a particular cell type, such as an antibody that recognizes an antigen on a specific cell type or a ligand that binds a specific receptor on a specific cell type. See Section 5.4 *supra* for examples of such heterologous polypeptides.

**[00223]** Non-influenza viruses containing/expressing a chimeric influenza hemagglutinin (HA) polypeptide described herein can be produced using techniques known to those skilled in the art. Non-influenza viruses containing a chimeric influenza hemagglutinin (HA) polypeptide described herein may be produced by supplying in *trans* the chimeric influenza hemagglutinin (HA) polypeptide during production of virions using techniques known to one skilled in the art. Alternatively, the replication of a parental non-influenza virus comprising a genome engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein in cells susceptible to infection with the virus wherein hemagglutinin function is provided in *trans* will produce progeny viruses containing the chimeric influenza hemagglutinin (HA) polypeptide.

**[00224]** Any virus type, subtype or strain including, but not limited to, naturally occurring strains, variants or mutants, mutagenized viruses, reassortants and/or genetically modified

viruses may be used as a non-influenza virus vector. In a specific embodiment, the parental non-influenza virus is not a naturally occurring virus. In another specific embodiment, the parental non-influenza virus is a genetically engineered virus. In certain embodiments, an enveloped virus is preferred for the expression of a membrane bound chimeric influenza hemagglutinin (HA) polypeptide described herein.

**[00225]** In an exemplary embodiment, the non-influenza virus vector is a Newcastle disease virus (NDV). In another embodiment, the non-influenza virus vector is a vaccinia virus. In another embodiment, the non-influenza virus vector is a baculovirus (such as, *e.g.,* BacMam [Invitrogen]). In other exemplary, non-limiting, embodiments, the non-influenza virus vector is adenovirus, adeno-associated virus (AAV), hepatitis B virus, retrovirus (such as, *e.g.*, a gammaretrovirus such as Mouse Stem Cell Virus (MSCV) genome or Murine Leukemia Virus (MLV), *e.g.*, Moloney murine leukemia virus, oncoretrovirus, or lentivirus), an alphavirus (*e.g.*, Venezuelan equine encephalitis virus), a rhabdovirus (such as vesicular stomatitis virus (VSV) or papillomaviruses), poxvirus (such as, e.g., vaccinia virus, a MVA-T7 vector, or fowlpox), metapneumovirus, measles virus, herpesvirus (such as herpes simplex virus), or foamyvirus. *See*, *e.g.*, Lawrie and Tumin, 1993, Cur. Opin. Genet. Develop. 3, 102-109 (retroviral vectors); Bett *et al.*, 1993, J. Virol. 67, 5911 (adenoviral vectors); Zhou *et al.*, 1994, J. Exp. Med. 179, 1867 (adeno-associated virus vectors); Dubensky *et al.*, 1996, J. Virol. 70, 508-519 (viral vectors from the pox family including vaccinia virus and the avian pox viruses and viral vectors from the alpha virus genus such as those derived from Sindbis and Semliki Forest Viruses); U.S. Pat. No. 5,643,576 (Venezuelan equine encephalitis virus); WO 96/34625 (VSV); Ohe *et al.*, 1995, Human Gene Therapy 6, 325-333; Woo *et al.*, WO 94/12629; Xiao & Brandsma, 1996, Nucleic Acids. Res. 24, 2630-2622 (papillomaviruses); and Bukreyev and Collins, 2008, Curr Opin Mol Ther. 10:46-55 (NDV), each of which is incorporated by reference herein in its entirety.

**[00226]** In a specific embodiment, the non-influenza virus vector is NDV. Any NDV type, subtype or strain may serve as the backbone that is engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein, including, but not limited to, naturally-occurring strains, variants or mutants, mutagenized viruses, reassortants and/or genetically engineered viruses. In a specific embodiment, the NDV that serves as the backbone for genetic engineering is a naturally-occurring strain. In certain embodiments, the NDV that serves as the backbone for genetic engineering is a lytic strain. In other embodiments, the NDV that serves as

the backbone for genetic engineering is a non-lytic strain. In certain embodiments, the NDV that serves as the backbone for genetic engineering is lentogenic strain. In some embodiments, the NDV that serves as the backbone for genetic engineering is a mesogenic strain. In other embodiments, the NDV that serves as the backbone for genetic engineering is a velogenic strain. Specific examples of NDV strains include, but are not limited to, the 73-T strain, Ulster strain, MTH-68 strain, Italien strain, Hickman strain, PV701 strain, Hitchner B1 strain, La Sota strain, YG97 strain, MET95 strain, and F48E9 strain. In a specific embodiment, the NDV that serves as the backbone for genetic engineering is the Hitchner B1 strain. In another specific embodiment, the NDV that serves as the backbone for genetic engineering is the La Sota strain.

**[00227]** In one embodiment, the NDV used as the backbone for a non-influenza virus vector is engineered to express a modified F protein in which the cleavage site of the F protein is replaced with one containing one or two extra arginine residues, allowing the mutant cleavage site to be activated by ubiquitously expressed proteases of the furin family. Specific examples of NDVs that express such a modified F protein include, but are not limited to, rNDV/F2aa and rNDV/F3aa. For a description of mutations introduced into a NDV F protein to produce a modified F protein with a mutated cleavage site, see, e.g., Park *et al.* (2006) "Engineered viral vaccine constructs with dual specificity: Avian influenza and Newcastle disease." PNAS USA 103: 8203-2808, which is incorporated herein by reference in its entirety.

**[00228]** In one embodiment, the non-influenza virus vector is a poxvirus. A poxvirus vector may be based on any member of the poxviridae, in particular, a vaccinia virus or an avipox virus (*e.g.*, such as canarypox, fowlpox, etc.) that provides suitable sequences for vaccine vectors. In a specific embodiment, the poxviral vector is a vaccinia virus vector. Suitable vaccinia viruses include, but are not limited to, the Copenhagen (VC-2) strain (Goebel, *et al.*, Virol 179: 247-266, 1990; Johnson, *et al.*, Virol. 196: 381-401, 1993), modified Copenhagen strain (NYVAC) (U.S. Pat. No. 6,265,189), the WYETH strain and the modified Ankara (MVA) strain (Antoine, *et al.*, Virol. 244: 365-396, 1998). Other suitable poxviruses include fowlpox strains such as ALVAC and TROVAC vectors that provide desirable properties and are highly attenuated (*see, e.g.*, U.S. Pat. No. 6,265,189; Tartaglia *et al.*, In AIDS Research Reviews, Koff, *et al.*, eds., Vol. 3, Marcel Dekker, N.Y., 1993; and Tartaglia *et al.*, 1990, Reviews in Immunology 10: 13-30, 1990).

**[00229]** Methods of engineering non-influenza viruses to express influenza polypeptides are well known in the art, as are methods for attenuating, propagating, and isolating and purifying

such viruses. For such techniques with respect to NDV vectors, *see*, *e.g.*, International Publication No. WO 01/04333; U.S. Patent Nos. 7,442,379, 6,146,642, 6,649,372, 6,544,785 and 7,384,774; Swayne *et al.* (2003). Avian Dis. 47:1047-1050; and Swayne *et al.* (2001). J. Virol. 11868-11873, each of which is incorporated by reference in its entirety. For such techniques with respect to poxviruses, *see*, *e.g.*, Piccini, *et al.*, Methods of Enzymology 153: 545-563, 1987; International Publication No. WO 96/11279; U.S. Pat. No. 4,769,330; U.S. Pat. No. 4,722,848; U.S. Pat. No. 4,769,330; U.S. Pat. No. 4,603,112; U.S. Pat. No. 5,110,587; U.S. Pat. No. 5,174,993; EP 83 286; EP 206 920; Mayr *et al.*, Infection 3: 6-14, 1975; and Sutter and Moss, Proc. Natl. Acad. Sci. USA 89: 10847-10851, 1992. In certain embodiments, the non-influenza virus is attenuated.

**[00230]** Exemplary considerations for the selection of a non-influenza virus vector, particularly for use in compositions for administration to a subject, are safety, low toxicity, stability, cell type specificity, and immunogenicity, particularly, antigenicity of the chimeric influenza hemagglutinin (HA) polypeptide described herein expressed by the non-influenza virus vector.

### 5.6 VIRUS-LIKE PARTICLES AND VIROSOMES

**[00231]** The chimeric influenza hemagglutinin (HA) polypeptides described herein (e.g., the chimeric influenza hemagglutinin (HA) polypeptides described in Section 5.1) can be incorporated into virus-like particle (VLP) vectors, e.g., purified/isolated VLPs. VLPs generally comprise a viral polypeptide(s) typically derived from a structural protein(s) of a virus. In some embodiments, the VLPs are not capable of replicating. In certain embodiments, the VLPs may lack the complete genome of a virus or comprise a portion of the genome of a virus. In some embodiments, the VLPs are not capable of infecting a cell. In some embodiments, the VLPs express on their surface one or more of viral (*e.g.*, virus surface glycoprotein) or non-viral (*e.g.*, antibody or protein) targeting moieties known to one skilled in the art or described herein. In some embodiments, the VLPs comprise a chimeric influenza hemagglutinin (HA) polypeptide described herein and a viral structural protein, such as HIV gag. In a specific embodiment, the VLPs comprise a chimeric influenza hemagglutinin (HA) polypeptide described herein and an HIV gag polypeptide.

**[00232]** Methods for producing and characterizing recombinantly produced VLPs have been described based on several viruses, including influenza virus (Bright *et al.* (2007) Vaccine. 25:3871), human papilloma virus type 1 (Hagnesee *et al.* (1991) J. Virol. 67:315), human papilloma virus type 16 (Kirnbauer *et al.* Proc. Natl. Acad. Sci. (1992)89:12180), HIV-1 (Haffer *et al.*, (1990) J. Virol. 64:2653), and hepatitis A (Winokur (1991) 65:5029), each of which is incorporated herein in its entirety. Methods for expressing VLPs that contain NDV proteins are provided by Pantua *et al.* (2006) J. Virol. 80:11062-11073, and in United States patent application Publication No. 20090068221, published March 12, 2009, each of which is incorporated in its entirety herein. In a specific embodiment, the VLPs comprising chimeric influenza hemagglutinin (HA) polypeptides described herein are generated using baculovirus. In other embodiments, the VLPs comprising chimeric influenza hemagglutinin (HA) polypeptide described herein are generated using 293T cells.

**[00233]** In specific embodiments, VLPs, e.g., VLPs comprising a chimeric influenza hemagglutinin (HA) polypeptide described herein, are expressed in cells (e.g., 293T cells). In certain embodiments, the VLPs are expressed in cells that express surface glycoproteins that comprise sialic acid. In accordance with such embodiments, the cells are cultured in the presence of neuraminidase (e.g., viral of bacterial neuraminidase). In certain embodiments, VLPs, e.g., VLPs comprising a chimeric influenza hemagglutinin (HA) polypeptide described herein, are expressed in cells that do not express surface glycoproteins that comprise sialic acid.

**[00234]** In a specific embodiment, a chimeric influenza hemagglutinin (HA) polypeptide described herein may be incorporated into a virosome. A virosome containing a chimeric influenza hemagglutinin (HA) polypeptide described herein may be produced using techniques known to those skilled in the art. For example, a virosome may be produced by disrupting a purified virus, extracting the genome, and reassembling particles with the viral proteins (*e.g.*, a chimeric influenza hemagglutinin (HA) polypeptide described herein) and lipids to form lipid particles containing viral proteins.

## 5.7 BACTERIAL VECTORS

**[00235]** In a specific embodiment, bacteria may be engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described in Section 5.1). Suitable bacteria for expression of a chimeric

influenza hemagglutinin (HA) polypeptide described herein include, but are not limited to, *Listeria*, *Salmonella*, *Shigella sp.*, *Mycobacterium tuberculosis*, *E. coli*, *Neisseria meningitides*, *Brucella abortus*, *Brucella melitensis*, *Borrelia burgdorferi*, *Lactobacillus, Campylobacter, Lactococcus, Bifidobacterium,* and *Francisella tularensis*. In a specific embodiment, the bacteria engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein are attenuated. Techniques for the production of bacteria engineered to express a heterologous polypeptide are known in the art and can be applied to the expression of a chimeric influenza hemagglutinin (HA) polypeptide described herein. *See, e.g.*, United States Patent Application Publication No. 20080248066, published October 9, 2008, and United States Patent Application Publication No. 20070207171, published September 6, 2007, each of which are incorporated by reference herein in their entirety. In certain embodiments, the bacterial vectors used herein possess the ability to perform N-linked glycosylation, e.g., such bacteria naturally possess N-glycosylation machinery (e.g., *Campylobacter*) or have been genetically engineered to possess N-glycosylation machinery.

## 5.8 GENERATION OF ANTIBODIES AGAINST CHIMERIC INFLUENZA HEMAGGLUTININ (HA) POLYPEPTIDES

**[00236]** The chimeric influenza hemagglutinin (HA) polypeptides described herein (e.g., the chimeric influenza hemagglutinin (HA) polypeptides described in Section 5.1), nucleic acids encoding such polypeptides, or vectors comprising such nucleic acids or polypeptides described herein may be used to elicit neutralizing antibodies against influenza, for example, against the stalk region of an influenza virus hemagglutinin polypeptide. In a specific embodiment, the chimeric influenza hemagglutinin (HA) polypeptides, nucleic acids encoding such polypeptides, or vectors comprising such nucleic acids or polypeptides described herein may be administered to a non-human subject (*e.g.*, a mouse, rabbit, rat, guinea pig, etc.) to induce an immune response that includes the production of antibodies which may be isolated using techniques known to one of skill in the art (*e.g.*, immunoaffinity chromatography, centrifugation, precipitation, etc.).

**[00237]** In certain embodiments, human antibodies directed against the chimeric influenza hemagglutinin (HA) polypeptides described herein can be generated using non-human subjects (e.g., transgenic mice) that are capable of producing human antibodies. For example, human antibodies can be produced using transgenic mice which are incapable of expressing functional

endogenous immunoglobulins, but which can express human immunoglobulin genes. For example, the human heavy and light chain immunoglobulin gene complexes may be introduced randomly or by homologous recombination into mouse embryonic stem cells. Alternatively, the human variable region, constant region, and diversity region may be introduced into mouse embryonic stem cells in addition to the human heavy and light chain genes. The mouse heavy and light chain immunoglobulin genes may be rendered non-functional separately or simultaneously with the introduction of human immunoglobulin loci by homologous recombination. In particular, homozygous deletion of the JH region prevents endogenous antibody production. The modified embryonic stem cells are expanded and microinjected into blastocysts to produce chimeric mice. The chimeric mice are then bred to produce homozygous offspring which express human antibodies. The human immunoglobulin transgenes harbored by the transgenic mice rearrange during B cell differentiation, and subsequently undergo class switching and somatic mutation. Thus, using such a technique, it is possible to produce therapeutically useful IgG, IgA, IgM and IgE antibodies. For an overview of this technology for producing human antibodies, see Lonberg and Huszar, Int. Rev. Immunol. 13:65-93 (1995). For a detailed discussion of this technology for producing human antibodies and human monoclonal antibodies and protocols for producing such antibodies, see, *e.g.,* PCT publications WO 98/24893; WO 92/01047; WO 96/34096; WO 96/33735; European Patent No. 0 598 877; U.S. Pat. Nos. 5,413,923; 5,625,126; 5,633,425; 5,569,825; 5,661,016; 5,545,806; 5,814,318; 5,885,793; 5,916,771; and 5,939,598, which are incorporated by reference herein in their entirety. Companies such as Abgenix, Inc. (Freemont, Calif.), Genpharm (San Jose, Calif.), and Medarex, Inc. (Princeton, N.J.) can be engaged to provide human antibodies directed against a selected antigen. In addition, non-human subjects may be transplanted with human peripheral blood leukocytes, splenocytes, or bone marrow (e.g., Trioma Techniques XTL) so that human antibodies that bind to a chimeric influenza hemagglutinin (HA) polypeptide described herein are generated.

**[00238]** Alternatively, the chimeric influenza hemagglutinin (HA) polypeptides described herein may be used to screen for antibodies from antibody libraries. For example, an isolated chimeric influenza hemagglutinin (HA) polypeptide may be immobilized to a solid support (*e.g.*, a silica gel, a resin, a derivatized plastic film, a glass bead, cotton, a plastic bead, a polystyrene bead, an alumina gel, or a polysaccharide, a magnetic bead), and screened for binding to

antibodies. As an alternative, the antibodies may be immobilized to a solid support and screened for binding to the isolated chimeric influenza hemagglutinin (HA) polypeptide. Any screening assay, such as a panning assay, ELISA, surface plasmon resonance, or other antibody screening assay known in the art may be used to screen for antibodies that bind to the chimeric influenza hemagglutinin (HA) polypeptide. The antibody library screened may be a commercially available antibody library, an *in vitro* generated library, or a library obtained by identifying and cloning or isolating antibodies from an individual infected with influenza. In particular embodiments, the antibody library is generated from a survivor of an influenza virus outbreak. Antibody libraries may be generated in accordance with methods known in the art. In a particular embodiment, the antibody library is generated by cloning the antibodies and using them in phage display libraries or a phagemid display library.

**[00239]** Antibodies identified in the methods described herein may be tested for neutralizing activity and lack of autoreactivity using the biological assays known in the art or described herein. In one embodiment, an antibody isolated from a non-human animal or an antibody library neutralizes a hemagglutinin polypeptide from more than one influenza subtype. In some embodiments, an antibody elicited or identified using a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, or a vector encoding such a nucleic acid or polypeptide neutralizes an influenza H3 virus. In some embodiments, an antibody elicited or identified using a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, or a vector comprising such a nucleic acid or polypeptide neutralizes 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, or 16 or more subtypes or strains of influenza virus. In one embodiment, the neutralizing antibody neutralizes one or more influenza A viruses and one or more influenza B viruses. In particular embodiments, the neutralizing antibody is not, or does not bind the same epitope as CR6261, CR6325, CR6329, CR6307, CR6323, 2A, D7, D8, F10, G17, H40, A66, D80, E88, E90, H98, C179 (produced by hybridoma FERM BP-4517; clones sold by Takara Bio, Inc. (Otsu, Shiga, Japan)), and/or AI3C (FERM BP-4516); or any other antibody described in Ekiert DC *et al.* (2009) Antibody Recognition of a Highly Conserved Influenza Virus Epitope. Science (published in Science Express February 26, 2009); Kashyap *et al.* (2008) Combinatorial antibody libraries from survivors of the Turkish H5N1 avian influenza outbreak reveal virus neutralization strategies. Proc Natl Acad Sci U S A 105: 5986-5991; Sui *et al.* (2009) Structural and functional

bases for broad-spectrum neutralization of avian and human influenza A viruses. Nat Struct Mol Biol 16: 265-273; U.S. Patent Nos. 5,589,174, 5,631,350, 6,337,070, and 6,720,409; International Application No. PCT/US2007/068983 published as International Publication No. WO 2007/134237; International Application No. PCT/US2008/075998 published as International Publication No. WO 2009/036157; International Application No. PCT/EP2007/059356 published as International Publication No. WO 2008/028946; and International Application No. PCT/US2008/085876 published as International Publication No. WO 2009/079259. In other embodiments, the neutralizing antibody is not an antibody described in Wang *et al.* (2010) "Broadly Protective Monoclonal Antibodies against H3 Influenza Viruses following Sequential Immunization with Different Hemagglutinins," PLOS Pathogens 6(2):1-9. In particular embodiments, the neutralizing antibody does not use the Ig VH1-69 segment. In some embodiments, the interaction of the neutralizing antibody with the antigen is not mediated exclusively by the heavy chain.

**[00240]** Antibodies identified or elicited using a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, or a vector comprising such a nucleic acid or polypeptide include immunoglobulin molecules and immunologically active portions of immunoglobulin molecules, *i.e.*, molecules that contain an antigen binding site that specifically binds to a hemagglutinin polypeptide. The immunoglobulin molecules may be of any type (*e.g.*, IgG, IgE, IgM, IgD, IgA and IgY), class (*e.g.*, $IgG_1$, $IgG_2$, $IgG_3$, $IgG_4$, $IgA_1$ and $IgA_2$) or subclass of immunoglobulin molecule. Antibodies include, but are not limited to, monoclonal antibodies, multispecific antibodies, human antibodies, humanized antibodies, chimeric antibodies, single-chain Fvs (scFv), single chain antibodies, Fab fragments, F(ab') fragments, disulfide-linked Fvs (sdFv), and anti-idiotypic (anti-Id) antibodies (including, *e.g.*, anti-Id antibodies to antibodies elicited or identified using a method described herein), and epitope-binding fragments of any of the above.

**[00241]** Antibodies elicited or identified using a chimeric influenza hemagglutinin (HA) polypeptide described herein, nucleic acids encoding such a polypeptide or a vector comprising such a nucleic acid or polypeptide may be used in diagnostic immunoassays, passive immunotherapy, and generation of antiidiotypic antibodies. The antibodies before being used in passive immunotherapy may be modified, e.g., the antibodies may be chimerized or humanized. *See*, *e.g.*, U.S. Patent Nos. 4,444,887 and 4,716,111; and International Publication Nos. WO

98/46645, WO 98/50433, WO 98/24893, WO 98/16654, WO 96/34096, WO 96/33735, and WO 91/10741, each of which is incorporated herein by reference in its entirety, for reviews on the generation of chimeric and humanized antibodies. In addition, the ability of the antibodies to neutralize hemagglutinin polypeptides and the specificity of the antibodies for the polypeptides may be tested prior to using the antibodies in passive immunotherapy.

**[00242]** Antibodies elicited or identified using a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, or a vector comprising such a nucleic acid or polypeptide may be used to monitor the efficacy of a therapy and/or disease progression. Any immunoassay system known in the art may be used for this purpose including, but not limited to, competitive and noncompetitive assay systems using techniques such as radioimmunoassays, ELISA (enzyme linked immunosorbent assays), "sandwich" immunoassays, precipitin reactions, gel diffusion precipitin reactions, immunodiffusion assays, agglutination assays, complement fixation assays, immunoradiometric assays, fluorescent immunoassays, protein A immunoassays and immunoelectrophoresis assays, to name but a few.

**[00243]** Antibodies elicited or identified using a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, or a vector comprising such a nucleic acid or polypeptide may be used in the production of antiidiotypic antibody. The antiidiotypic antibody can then in turn be used for immunization, in order to produce a subpopulation of antibodies that bind a particular antigen of influenza, *e.g.*, a neutralizing epitope of a hemagglutinin polypeptide (Jerne, 1974, Ann. Immunol. (Paris) 125c:373; Jerne *et al.*, 1982, EMBO J. 1:234, incorporated herein by reference in its entirety). Antibodies elicited or identified using a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, or a vector comprising such a nucleic acid or polypeptide may be used in the design of mimotopes. The mimotope can then in turn be used for immunization, in order to produce a subpopulation of antibodies that bind to the particular antigen of influenza encoded in the mimotope, *e.g.*, a neutralizing epitope of a hemagglutinin polypeptide (Jerne, 1974, Ann. Immunol. (Paris) 125c:373; Jerne *et al.*, 1982, EMBO J. 1:234, incorporated herein by reference in its entirety).

## 5.9 STIMULATION OF CELLS WITH CHIMERIC INFLUENZA HEMAGGLUTININ (HA) POLYPEPTIDES

**[00244]** In another aspect, provided herein are methods for stimulating cells *ex vivo* with a chimeric influenza hemagglutinin (HA) polypeptide described herein (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described in Section 5.1). Such cells, *e.g.*, dendritic cells, may be used *in vitro* to generate antibodies against the chimeric influenza hemagglutinin (HA) polypeptide or may themselves be administered to a subject by, *e.g.*, an adoptive transfer technique known in the art. *See*, *e.g.*, United States patent application Publication No. 20080019998, published January 24, 2008, which is incorporated herein by reference in its entirety, for a description of adoptive transfer techniques. In certain embodiments, when cells that have been stimulated *ex vivo* with a chimeric influenza hemagglutinin (HA) polypeptide described herein are administered to a subject, the cells are not mammalian cells (e.g., CB-1 cells).

**[00245]** In one non-limiting example, a vector, *e.g.*, an influenza virus vector, engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein can be used to generate dendritic cells (DCs) that express the chimeric influenza hemagglutinin (HA) polypeptide and display immunostimulatory properties directed against an influenza virus hemagglutinin polypeptide. Such DCs may be used to expand memory T cells and are potent stimulators of T cells, including chimeric influenza hemagglutinin (HA) polypeptide-specific cytotoxic T lymphocyte clones. See Strobel *et al.*, 2000, Human Gene Therapy 11:2207-2218, which is incorporated herein by reference in its entirety.

**[00246]** A chimeric influenza hemagglutinin (HA) polypeptide described herein may be delivered to a target cell in any way that allows the polypeptide to contact the target cell, *e.g.*, a DC, and deliver the polypeptide to the target cell. In certain embodiments, the chimeric influenza hemagglutinin (HA) polypeptide described herein is delivered to a subject, as described herein. In some such embodiments, cells contacted with the polypeptide may be isolated and propagated.

**[00247]** In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide described herein is delivered to a target cell *in vitro*. Techniques known to one of skill in the art may be used to deliver the polypeptide to target cells. For example, target cells may be contacted with the polypeptide in a tissue culture plate, tube or other container. The polypeptide may be suspended in media and added to the wells of a culture plate, tube or other container. The media containing the polypeptide may be added prior to plating of the cells or after the cells

have been plated. The target cells are preferably incubated with the polypeptide for a sufficient amount of time to allow the polypeptide to contact the cells. In certain embodiments, the cells are incubated with the polypeptide for about 1 hour or more, about 5 hours or more, about 10 hours or more, about 12 hours or more, about 16 hours or more, about 24, hours or more, about 48 hours or more, about 1 hour to about 12 hours, about 3 hours to about 6 hours, about 6 hours to about 12 hours, about 12 hours to about 24 hours, or about 24 hours to about 48 hours. In certain embodiments, wherein the chimeric influenza hemagglutinin (HA) polypeptide is in a virus, the contacting of the target cells comprises infecting the cells with the virus.

**[00248]** The target cells may be from any species, including, e.g., humans, mice, rats, rabbits and guinea pigs. In some embodiments, target cells are DCs obtained from a healthy subject or a subject in need of treatment. In certain embodiments, target cells are DCs obtained from a subject in whom it is desired to stimulate an immune response to the polypeptide. Methods of obtaining cells from a subject are well known in the art.

## 5.10 COMPOSITIONS

**[00249]** The nucleic acids, vectors, polypeptides, bacteria, antibodies, and/or cells described herein (sometimes referred to herein as "active compounds") may be incorporated into compositions. In a specific embodiment, the compositions are pharmaceutical compositions, such as immunogenic compositions (*e.g.*, vaccine formulations). The pharmaceutical compositions provided herein can be in any form that allows for the composition to be administered to a subject. In a specific embodiment, the pharmaceutical compositions are suitable for veterinary and/or human administration. The compositions may be used in methods of preventing or treating an influenza virus disease.

**[00250]** In one embodiment, a pharmaceutical composition comprises a chimeric influenza hemagglutinin (HA) polypeptide described herein (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described in Section 5.1), in an admixture with a pharmaceutically acceptable carrier. In another embodiment, a pharmaceutical composition comprises a nucleic acid encoding a chimeric influenza hemagglutinin (HA) polypeptide described herein (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described in Section 5.1), in an admixture with a pharmaceutically acceptable carrier. In another embodiment, a pharmaceutical composition comprises an expression vector comprising a nucleic acid encoding a chimeric influenza

hemagglutinin (HA) polypeptide described herein (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described in Section 5.1), in an admixture with a pharmaceutically acceptable carrier. In another embodiment, a pharmaceutical composition comprises an influenza virus or non-influenza virus containing a chimeric influenza hemagglutinin (HA) polypeptide described herein (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described in Section 5.1), in an admixture with a pharmaceutically acceptable carrier. In another embodiment, a pharmaceutical composition comprises an influenza virus or non-influenza virus having a genome engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described in Section 5.1), in admixture with a pharmaceutically acceptable carrier. In another embodiment, a pharmaceutical composition comprises a virus-like particle or virosome containing a chimeric influenza hemagglutinin (HA) polypeptide described herein (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described in Section 5.1), in an admixture with a pharmaceutically acceptable carrier. In another embodiment, a pharmaceutical composition comprises a bacteria expressing or engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described in Section 5.1), in an admixture with a pharmaceutically acceptable carrier. In another embodiment, a pharmaceutical composition comprises cells stimulated with a chimeric influenza hemagglutinin (HA) polypeptide described herein (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described in Section 5.1), in an admixture with a pharmaceutically acceptable carrier.

**[00251]** In some embodiments, a pharmaceutical composition may comprise one or more other therapies in addition to a therapy that utilizes a chimeric influenza hemagglutinin (HA) polypeptide described herein.

**[00252]** As used herein, the term "pharmaceutically acceptable" means approved by a regulatory agency of the Federal or a state government or listed in the U.S. Pharmacopeia or other generally recognized pharmacopeiae for use in animals, and more particularly in humans. The term "carrier" refers to a diluent, adjuvant, excipient, or vehicle with which the pharmaceutical composition is administered. Saline solutions and aqueous dextrose and glycerol solutions can also be employed as liquid carriers, particularly for injectable solutions. Suitable excipients include starch, glucose, lactose, sucrose, gelatin, malt, rice, flour, chalk, silica gel, sodium stearate, glycerol monostearate, talc, sodium chloride, dried skim milk, glycerol,

propylene, glycol, water, ethanol and the like. Examples of suitable pharmaceutical carriers are described in "Remington's Pharmaceutical Sciences" by E.W. Martin. The formulation should suit the mode of administration.

**[00253]** In a specific embodiment, pharmaceutical compositions are formulated to be suitable for the intended route of administration to a subject. For example, the pharmaceutical composition may be formulated to be suitable for parenteral, oral, intradermal, transdermal, colorectal, intraperitoneal, and rectal administration. In a specific embodiment, the pharmaceutical composition may be formulated for intravenous, oral, intraperitoneal, intranasal, intratracheal, subcutaneous, intramuscular, topical, intradermal, transdermal or pulmonary administration. In a specific embodiment, the pharmaceutical composition is formulated for intranasal administration. In another specific embodiment, the pharmaceutical composition is formulated for intramuscular administration.

**[00254]** In certain embodiments, biodegradable polymers, such as ethylene vinyl acetate, polyanhydrides, polyethylene glycol (PEGylation), polymethyl methacrylate polymers, polylactides, poly(lactide-co-glycolides), polyglycolic acid, collagen, polyorthoesters, and polylactic acid, may be used as carriers. In some embodiments, the active compounds are prepared with carriers that increase the protection of the compound against rapid elimination from the body, such as a controlled release formulation, including implants and microencapsulated delivery systems. Methods for preparation of such formulations will be apparent to those skilled in the art. Liposomes or micelles can also be used as pharmaceutically acceptable carriers. These can be prepared according to methods known to those skilled in the art, for example, as described in U.S. Pat. No. 4,522,811. In certain embodiments, the pharmaceutical compositions comprise one or more adjuvants.

**[00255]** In specific embodiments, the immunogenic compositions described herein are monovalent formulations, e.g., monovalent formulations comprising a cH5/1 chimeric influenza hemagglutinin polypeptide described herein, a cH5/3 chimeric influenza hemagglutinin polypeptide described herein, a cH7/3 chimeric influenza hemagglutinin polypeptide described herein, a cH5/B chimeric influenza hemagglutinin polypeptide described herein, a cH7/B chimeric influenza hemagglutinin polypeptide described herein, a cHB/B chimeric influenza hemagglutinin polypeptide described herein, or a cH4/3 chimeric influenza hemagglutinin polypeptide described herein.

**[00256]** In other specific embodiments, the immunogenic compositions described herein are multivalent formulations, eg., bivalent and trivalent formulations. In one example, a multivalent formulation comprises more than one vector expressing a chimeric influenza hemagglutinin (HA) polypeptide described herein. In certain embodiments, a multivalent formulation may comprise one or more different chimeric influenza hemagglutinin (HA) polypeptides described herein expressed using a single vector. In certain embodiments, a multivalent formulation comprises different chimeric influenza hemagglutinin polypeptides, wherein each chimeric influenza hemagglutinin polypeptide comprises the same influenza hemagglutinin globular head domain and different influenza hemagglutinin stem domains. The different influenza hemagglutinin stem domains can be from different influenza virus strains, subtypes, or groups. For example, a bivalent formulation may comprise two chimeric influenza hemagglutinin polypeptides, wherein the two chimeric influenza hemagglutinin polypeptides comprise the same influenza hemagglutinin globular head domain and different influenza hemagglutinin stem domains from two different influenza viruses. In another example, a trivalent formulation may comprise three chimeric influenza hemagglutinin polypeptides wherein the three chimeric influenza hemagglutinin polypeptides comprise the same influenza hemagglutinin globular head domains and different influenza hemagglutinin stem domains from three different influenza viruses. In specific embodiments, a bivalent vaccine formulation provided herein may comprise a combination of a cH5/1 chimeric influenza hemagglutinin polypeptide described herein and a cH5/3 chimeric influenza hemagglutinin polypeptide described herein; or a combination of a cH5/1 chimeric influenza hemagglutinin polypeptide described herein and a cH7/3 chimeric influenza hemagglutinin polypeptide described herein. In specific embodiments, a trivalent vaccine formulation provided herein may comprise (i) a combination of a cH5/1 chimeric influenza hemagglutinin polypeptide described herein and a cH5/3 chimeric influenza hemagglutinin polypeptide described herein and either of a cH5/B, a cH7/B, or a cB/B chimeric influenza hemagglutinin polypeptide described herein; or (ii) a combination of a cH5/1 chimeric influenza hemagglutinin polypeptide described herein and a cH7/3 chimeric influenza hemagglutinin polypeptide described herein and either of a cH5/B, a cH7/B, or a cB/B chimeric influenza hemagglutinin polypeptide described herein. In certain embodiments a bivalent or trivalent vaccine formulation comprises a cH4/3 chimeric influenza hemagglutinin polypeptide described herein.

**[00257]** In certain embodiments, the pharmaceutical compositions described herein additionally comprise a preservative, e.g., the mercury derivative thimerosal. In a specific embodiment, the pharmaceutical compositions described herein comprises 0.001% to 0.01% thimerosal. In other embodiments, the pharmaceutical compositions described herein do not comprise a preservative. In a specific embodiment, thimerosal is used during the manufacture of a pharmaceutical composition described herein and the thimerosal is removed via purification steps following production of the pharmaceutical composition, i.e., the pharmaceutical composition contains trace amounts of thimerosal (<0.3 μg of mercury per dose after purification; such pharmaceutical compositions are considered thimerosal-free products).

**[00258]** In certain embodiments, the pharmaceutical compositions described herein additionally comprise egg protein (e.g., ovalbumin or other egg proteins). The amount of egg protein in the pharmaceutical compositions described herein may range from about 0.0005 to about 1.2. μg of egg protein to 1 ml of pharmaceutical composition. In other embodiments, the pharmaceutical compositions described herein do not comprise egg protein.

**[00259]** In certain embodiments, the pharmaceutical compositions described herein additionally comprise one or more antimicrobial agents (e.g., antibiotics) including, but not limited to gentamicin, neomycin, polymyxin (e.g., polymyxin B), and kanamycin, streptomycin. In other embodiments, the pharmaceutical compositions described herein do not comprise any antibiotics.

**[00260]** In certain embodiments, the pharmaceutical compositions described herein additionally comprise one or more components used to inactivate a virus, e.g., formalin or formaldehyde or a detergent such as sodium deoxycholate, octoxynol 9 (Triton X-100), and octoxynol 10. In other embodiments, the pharmaceutical compositions described herein do not comprise any components used to inactivate a virus.

**[00261]** In certain embodiments, the pharmaceutical compositions described herein additionally comprise gelatin. In other embodiments, the pharmaceutical compositions described herein do not comprise gelatin.

**[00262]** In certain embodiments, the pharmaceutical compositions described herein additionally comprise one or more buffers, e.g., phosphate buffer and sucrose phosphate glutamate buffer. In other embodiments, the pharmaceutical compositions described herein do not comprise buffers.

**[00263]** In certain embodiments, the pharmaceutical compositions described herein additionally comprise one or more salts, e.g., sodium chloride, calcium chloride, sodium phosphate, monosodium glutamate, and aluminum salts (e.g., aluminum hydroxide, aluminum phosphate, alum (potassium aluminum sulfate), or a mixture of such aluminum salts). In other embodiments, the pharmaceutical compositions described herein do not comprise salts.

**[00264]** In specific embodiments, the pharmaceutical compositions described herein are low-additive influenza virus vaccines, i.e., the pharmaceutical compositions do not comprise one or more additives commonly found in influenza virus vaccines. Low-additive influenza vaccines have been described (see, e.g., International Aplication No. PCT/IB2008/002238 published as International Publication No. WO 09/001217 which is herein incorporated by reference in its entirety).

**[00265]** The pharmaceutical compositions described herein can be included in a container, pack, or dispenser together with instructions for administration.

**[00266]** The pharmaceutical compositions described herein can be stored before use, e.g., the pharmaceutical compositions can be stored frozen (e.g., at about -20˚C or at about -70˚C); stored in refrigerated conditions (e.g., at about 4˚C); or stored at room temperature (see International Aplication No. PCT/IB2007/001149 published as International Publication No. WO 07/110776, which is herein incorporated by reference in its entirety, for methods of storing compositions comprising influenza vaccines without refrigeration).

**[00267]** In certain embodiments, when the active compound in a pharmaceutical composition described herein is a cell engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein, the cells in the pharmaceutical composition are not mammalian cells (e.g., CB-1 cells).

### 5.10.1 Subunit Vaccines

**[00268]** In a specific embodiment, provided herein are subunit vaccines comprising a chimeric influenza hemagglutinin (HA) polypeptide described herein. In some embodiments, a subunit vaccine comprises a chimeric influenza hemagglutinin (HA) polypeptide described herein and one or more surface glycoproteins (*e.g.*, influenza virus neuraminidase), other targeting moieties, or adjuvants. In specific embodiments, a subunit vaccine comprises a single chimeric influenza hemagglutinin (HA) polypeptide described herein. In other embodiments, a subunit vaccine comprises two, three, four or more chimeric influenza hemagglutinin (HA) polypeptides

described herein. In specific embodiments, the chimeric influenza hemagglutinin (HA) polypeptides used in a subunit vaccine are not membrane-bound, *i.e.*, are soluble.

**[00269]** The subunit vaccines provided herein comprise an effective amount of chimeric influenza hemagglutinin (HA) polypeptide. In certain embodiments, the subunit vaccines provided herein comprise about 5, 6, 7, 8, 9, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, 65, 70, 75, 80, 85, 90, 95, 100, 105, 110, 115, 120, 125, 130, 135, 140, 145, or 150 μg of one or more chimeric influenza hemagglutinin (HA) polypeptides described herein. In certain embodiments, the subunit vaccines provided herein comprise about 5-10, 10-20, 20-30, 30-40, 40-50, 50-60, 60- 70, 70-80, 80-90, 90-100, 100-110, 110-120, 120-130, 130-140, or 140-150 μg of one or more chimeric influenza hemagglutinin (HA) polypeptides described herein.

**[00270]** In a specific embodiment, a monovalent subunit vaccine provided herein comprises between 7.5 μg to 90 μg of a chimeric influenza hemagglutinin (HA) polypeptide described herein. In another specific embodiment, a bivalent subunit vaccine provided herein comprises between 7.5 μg to 90 μg of a first chimeric influenza hemagglutinin (HA) polypeptide described herein and between 7.5 μg to 90 μg of a second chimeric influenza hemagglutinin (HA) polypeptide described herein. In another specific embodiment, a trivalent subunit vaccine provided herein comprises between 7.5 μg to 90 μg of a first chimeric influenza hemagglutinin (HA) polypeptide described herein, between 7.5 μg to 90 μg of a second chimeric influenza hemagglutinin (HA) polypeptide described herein, and between 7.5 μg to 90 μg of a third chimeric influenza hemagglutinin (HA) polypeptide described herein.

**[00271]** In certain embodiments, provided herein are subunit vaccines comprising about 10 μg to about 60 μg of one or more chimeric influenza hemagglutinin (HA) polypeptides described herein, about 0.001% to 0.01% thimerosal, about 0.1 μg to about 1.0 μg chicken egg protein, about 1.0 μg to about 5.0 μg polymyxin, about 1.0 μg to about 5.0 μg neomycin, about 0.1 μg to about 0.5 μg betapropiolactone, and about .001 to about .05 % w/v of nonylphenol ethoxylate per dose.

**[00272]** In a specific embodiment, a subunit vaccine provided herein comprises or consists of a 0.5 ml dose that comprises 45 μg of a chimeric influenza hemagglutinin (HA) polypeptide described herein, ≤ 1.0 μg of mercury (from thimerosal), ≤ 1.0 μg chicken egg protein (i.e., ovalbumin), ≤ 3.75 μg polymyxin, and ≤ 2.5 μg neomycin. In some embodiments, a subunit vaccine provided herein additionally comprises or consists of not more than 0.5 μg

betapropiolactone, and not more than 0.015 % w/v of nonylphenol ethoxylate per dose. In some embodiments, the 0.5 ml dose subunit vaccine is packaged in a pre-filled syringe.

**[00273]** In a specific embodiment, a subunit vaccine provided herein consists of a 5.0 ml multidose vial (0.5 ml per dose) that comprises 45 μg of a chimeric influenza hemagglutinin (HA) polypeptide described herein, 25.0 μg of mercury (from thimerosal), ≤ 1.0 μg chicken egg protein (i.e., ovalbumin), ≤ 3.75 μg polymyxin, and ≤ 2.5 μg neomycin. In some embodiments, a subunit vaccine provided herein additionally comprises or consists of not more than 0.5 μg betapropiolactone, and not more than 0.015 % w/v of nonylphenol ethoxylate per dose.

**[00274]** In a specific embodiment, the subunit vaccine is prepared using influenza virus that was propagated in embryonated chicken eggs (i.e., the components of the subunit vaccine (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described herein) are isolated from virus that was propagated in embryonated chicken eggs). In another specific embodiment, the subunit vaccine is prepared using influenza virus that was not propagated in embryonated chicken eggs (i.e., the components of the subunit vaccine (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described herein) are isolated from virus that was not propagated in embryonated chicken eggs). In another specific embodiment, the subunit vaccine is prepared using influenza virus that was propagated in mammalian cells, e.g., immortalized human cells (see, e.g., International Application No. PCT/EP2006/067566 published as International Publication No. WO 07/045674 which is herein incorporated by reference in its entirety), canine kidney cells such as MDCK cells (see, e.g., International Application No. PCT/IB2007/003536 published as International Publication No. WO 08/032219 which is herein incorporated by reference in its entirety), Vero cells, PerC.6 cells, or duck cells such as EB66 cells (i.e., the components of the subunit vaccine (e.g., a chimeric influenza hemagglutinin (HA) polypeptide) are isolated from virus that was propagated in mammalian cells). In another specific embodiment, the chimeric influenza hemagglutinin (HA) polypeptides in the subunit vaccines provided herein are prepared using an expression vector, *e.g.*, a viral vector, plant vector or a bacterial vector (i.e., the chimeric influenza hemagglutinin (HA) polypeptide in the subunit vaccine are obtained/isolated from an expression vector).

**[00275]** In a specific embodiment, provided herein is a monovalent subunit vaccine comprising a chimeric influenza hemagglutinin (HA) polypeptide described herein. In a specific embodiment, provided herein is a monovalent subunit vaccine comprising a cH5/1 chimeric

influenza hemagglutinin polypeptide (e.g., a cH5/1 chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent subunit vaccine comprising a cH5/3 chimeric influenza hemagglutinin polypeptide (e.g., a cH5/3 chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent subunit vaccine comprising a cH7/3 chimeric influenza hemagglutinin polypeptide (e.g., a cH7/3 chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent subunit vaccine comprising a cH5/B chimeric influenza hemagglutinin polypeptide (e.g., a cH5/B chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent subunit vaccine comprising a cH7/B chimeric influenza hemagglutinin polypeptide (e.g., a cH7/1 chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent subunit vaccine comprising a cB/B chimeric influenza hemagglutinin polypeptide (e.g., a B/B chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent subunit vaccine comprising a cH4/3 chimeric influenza virus hemagglutinin polypeptide (*e.g.*, a cH4/3 chimeric influenza hemagglutinin polypeptide described in Section 5.1).

**[00276]** In specific embodiments, provided herein are bivalent subunit vaccines comprising a chimeric influenza hemagglutinin (HA) polypeptide described herein. In certain embodiments, provided herein is a bivalent subunit vaccine comprising two chimeric influenza hemagglutinin polypeptides, wherein the two chimeric influenza hemagglutinin polypeptides comprise the same influenza hemagglutinin globular head domain from an influenza virus and each of the two chimeric influenza hemagglutinin polypeptides comprises a different influenza hemagglutinin stem domain from two different influenza viruses. In certain embodiments, the influenza hemagglutinin stem domains are from two different influenza strains, subtypes, or groups. In a specific embodiment, provided herein is a bivalent subunit vaccine comprising a cH5/1 chimeric influenza hemagglutinin polypeptide and a cH5/3 chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent subunit vaccine comprising a cH5/1 chimeric influenza hemagglutinin polypeptide and a cH7/3 chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent subunit vaccine comprising a cH5/1 chimeric influenza hemagglutinin polypeptide and a cH5/B

chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent subunit vaccine comprising a cH5/1 chimeric influenza hemagglutinin polypeptide and a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent subunit vaccine comprising a cH5/1 chimeric influenza hemagglutinin polypeptide and a cB/B chimeric influenza hemagglutinin polypeptide.

**[00277]** In another specific embodiment, provided herein is a bivalent subunit vaccine comprising a cH5/3 chimeric influenza hemagglutinin polypeptide and a cH7/3 chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent subunit vaccine comprising a cH5/3 chimeric influenza hemagglutinin polypeptide and a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent subunit vaccine comprising a cH5/3 chimeric influenza hemagglutinin polypeptide and a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent subunit vaccine comprising a cH5/3 chimeric influenza hemagglutinin polypeptide and a cB/B chimeric influenza hemagglutinin polypeptide.

**[00278]** In another specific embodiment, provided herein is a bivalent subunit vaccine comprising a cH7/3 chimeric influenza hemagglutinin polypeptide and a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent subunit vaccine comprising a cH7/3 chimeric influenza hemagglutinin polypeptide and a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent subunit vaccine comprising a cH7/3 chimeric influenza hemagglutinin polypeptide and a cB/B chimeric influenza hemagglutinin polypeptide.

**[00279]** In another specific embodiment, provided herein is a bivalent subunit vaccine comprising a cH5/B chimeric influenza hemagglutinin polypeptide and a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent subunit vaccine comprising a cH5/B chimeric influenza hemagglutinin polypeptide and a cB/B chimeric influenza hemagglutinin polypeptide.

**[00280]** In another specific embodiment, provided herein is a bivalent subunit vaccine comprising a cH7/B chimeric influenza hemagglutinin polypeptide and a cB/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent subunit vaccine comprising a cH4/3 chimeric hemagglutinin polypeptide described herein.

**[00281]** In specific embodiments, provided herein are trivalent subunit vaccines comprising viruses that contain and/or comprise a genome that encodes a chimeric influenza hemagglutinin (HA) polypeptide described herein. In certain embodiments, provided herein is a trivalent subunit vaccine comprising three chimeric influenza hemagglutinin polypeptides, wherein the three chimeric influenza hemagglutinin polypeptides comprise the same influenza hemagglutinin globular head domain from an influenza virus and each of the three chimeric influenza hemagglutinin polypeptides comprise a different influenza hemagglutinin stem domain from three different influenza viruses. In certain embodiments, the influenza hemagglutinin stem domains are from three different influenza virus strains, subtypes, or groups. In a specific embodiment, provided herein is a trivalent subunit vaccine comprising a cH5/1 chimeric influenza hemagglutinin polypeptide, a cH5/3 chimeric influenza hemagglutinin polypeptide, and a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent subunit vaccine comprising a cH5/1 chimeric influenza hemagglutinin polypeptide, a cH5/3 chimeric influenza hemagglutinin polypeptide, and a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent subunit vaccine comprising a cH5/1 chimeric influenza hemagglutinin polypeptide, a cH5/3 chimeric influenza hemagglutinin polypeptide, and a cB/B chimeric influenza hemagglutinin polypeptide.

**[00282]** In another specific embodiment, provided herein is a trivalent subunit vaccine comprising a cH5/1 chimeric influenza hemagglutinin polypeptide, a cH7/3 chimeric influenza hemagglutinin polypeptide, and a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent subunit vaccine comprising a cH5/1 chimeric influenza hemagglutinin polypeptide, a cH7/3 chimeric influenza hemagglutinin polypeptide, and a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent subunit vaccine comprising a cH5/1 chimeric influenza hemagglutinin polypeptide, a cH7/3 chimeric influenza hemagglutinin polypeptide, and a cB/B chimeric influenza hemagglutinin polypeptide. In certain embodiments, a trivalent subunit vaccine comprises a cH4/3 chimeric influenza hemagglutinin described herein.

**[00283]** In a specific embodiment, a subunit vaccine provided herein does not comprise a cH5/3 chimeric influenza hemagglutinin polypeptide comprising the globular head domain of A/Vietnam/1203/2004 (H5). In another specific embodiment, a subunit vaccine provided herein

does not comprise cH5/3 chimeric influenza hemagglutinin polypeptide comprising the stem domain of A/Perth/16/2009 (H3).

**[00284]** In a specific embodiment, a subunit vaccine provided herein does not comprise a cH7/3 chimeric influenza hemagglutinin polypeptide comprising the globular head domain of A/mallard/Alberta/24/2001 (H7). In another specific embodiment, a subunit vaccine provided herein does not comprise a cH7/3 chimeric influenza hemagglutinin polypeptide comprising the stem domain of A/Perth/16/2009 (H3).

### 5.10.2 Live Virus Vaccines

**[00285]** In one embodiment, provided herein are immunogenic compositions (*e.g.*, vaccines) comprising live virus containing a chimeric influenza hemagglutinin (HA) polypeptide described herein. In another embodiment, provided herein are immunogenic compositions (*e.g.*, vaccines) comprising live virus that is engineered to encode a chimeric influenza hemagglutinin (HA) polypeptide described herein, which is expressed by progeny virus produced in the subjects administered the compositions. In specific embodiments, the chimeric influenza hemagglutinin (HA) polypeptide is membrane-bound. In other specific embodiments, the chimeric influenza hemagglutinin (HA) polypeptide is not membrane-bound, *i.e.*, it is soluble. In particular embodiments, the live virus is an influenza virus, such as described in Section 5.4, *supra*. In other embodiments, the live virus is a non-influenza virus, such as described in Section 5.5, *supra*. In some embodiments, the live virus is attenuated. In some embodiments, an immunogenic composition comprises two, three, four or more live viruses containing or engineered to express two, three, four or more different chimeric influenza hemagglutinin (HA) polypeptide described herein.

**[00286]** In certain embodiments, provided herein are immunogenic compositions (*e.g.*, vaccines) comprising about $10^5$ to about $10^{10}$ fluorescent focus units (FFU) of live attenuated influenza virus containing one or more chimeric influenza hemagglutinin (HA) polypeptide described herein, about 0.1 to about 0.5 mg monosodium glutamate, about 1.0 to about 5.0 mg hydrolyzed procine gelatin, about 1.0 to about 5.0 mg arginine, about 10 to about 15 mg sucrose, about 1.0 to about 5.0 mg dibasic potassium phosphate, about 0.5 to about 2.0 mg monobasic potassium phosphate, and about 0.001 to about 0.05 μg/ml gentamicin sulfate per dose. In some embodiments, the immunogenic compositions (*e.g.*, vaccines) are packaged as pre-filled sprayers containing single 0.2 ml doses.

**[00287]** In a specific embodiment, provided herein are immunogenic compositions (*e.g.*, vaccines) comprising $10^{6.5}$ to $10^{7.5}$ FFU of live attenuated influenza virus containing one or more chimeric influenza hemagglutinin (HA) polypeptide described herein, 0.188 mg monosodium glutamate, 2.0 mg hydrolyzed procine gelatin, 2.42 mg arginine, 13.68 mg sucrose, 2.26 mg dibasic potassium phosphate, 0.96 mg monobasic potassium phosphate, and < 0.015 μg/ml gentamicin sulfate per dose. In some embodiments, the immunogenic compositions (*e.g.*, vaccines) are packaged as pre-filled sprayers containing single 0.2 ml doses.

**[00288]** In a specific embodiment, the live virus that contains a chimeric influenza hemagglutinin (HA) polypeptide described herein is propagated in embryonated chicken eggs before its use in an immunogenic composition described herein. In another specific embodiment, the live virus that contains a chimeric influenza hemagglutinin (HA) polypeptide described herein is not propagated in embryonated chicken eggs before its use in an immunogenic composition described herein. In another specific embodiment, the live virus that contains a chimeric influenza hemagglutinin (HA) polypeptide described herein is propagated in mammalian cells, e.g., immortalized human cells (see, e.g., International Application No. PCT/EP2006/067566 published as International Publication No. WO 07/045674 which is herein incorporated by reference in its entirety), canine kidney cells such as MDCK cells (see, e.g., International Application No. PCT/IB2007/003536 published as International Publication No. WO 08/032219 which is herein incorporated by reference in its entirety), Vero cells, PerC.6 cells, or duck cells such as EB66 cells before its use in an immunogenic composition described herein.

**[00289]** An immunogenic composition comprising a live virus for administration to a subject may be preferred because multiplication of the virus in the subject may lead to a prolonged stimulus of similar kind and magnitude to that occurring in natural infections, and therefore, confer substantial, long lasting immunity.

**[00290]** In a specific embodiment, provided herein is a monovalent live virus vaccine comprising a chimeric influenza hemagglutinin (HA) polypeptide described herein. In a specific embodiment, provided herein is a monovalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide (e.g., a cH5/1 chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent live virus vaccine comprising a

virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide (e.g., a cH5/3 chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide (e.g., a cH7/3 chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide (e.g., a cH5/B chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide (e.g., a cH7/1 chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide (e.g., a B/B chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH4/3 chimeric influenza hemagglutinin.

**[00291]** In specific embodiments, provided herein are bivalent live virus vaccines comprising viruses that contain and/or comprise a genome that encodes a chimeric influenza hemagglutinin (HA) polypeptide described herein. In certain embodiments, provided herein is a bivalent live virus vaccine comprising two chimeric influenza hemagglutinin polypeptides, wherein the two chimeric influenza hemagglutinin polypeptides comprise the same influenza hemagglutinin globular head domain from an influenza virus and each of the two chimeric influenza hemagglutinin polypeptides comprises a different influenza hemagglutinin stem domain from two different influenza viruses. In certain embodiments, the influenza hemagglutinin stem domains are from two different influenza strains, subtypes, or groups. In a specific embodiment, provided herein is a bivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent live virus vaccine

comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide.

**[00292]** In another specific embodiment, provided herein is a bivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide.

**[00293]** In another specific embodiment, provided herein is a bivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric

influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide.

**[00294]** In another specific embodiment, provided herein is a bivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide.

**[00295]** In another specific embodiment, provided herein is a bivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH4/3 chimeric influenza hemagglutinin polypeptide.

**[00296]** In specific embodiments, provided herein are trivalent live virus vaccines comprising viruses that contain and/or comprise a genome that encodes a chimeric influenza hemagglutinin (HA) polypeptide described herein. In certain embodiments, provided herein is a trivalent live virus vaccine comprising three chimeric influenza hemagglutinin polypeptides, wherein the three chimeric influenza hemagglutinin polypeptides comprise the same influenza hemagglutinin globular head domain from an influenza virus and each of the three chimeric influenza hemagglutinin polypeptides comprise a different influenza hemagglutinin stem domain from three different influenza viruses. In certain embodiments, the influenza hemagglutinin stem

domains are from three different influenza virus strains, subtypes, or groups. In a specific embodiment, provided herein is a trivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide.

**[00297]** In another specific embodiment, provided herein is a trivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide. In certain embodiments, provided herein is

a trivalent live virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH4/3 chimeric influenza hemagglutinin polypeptide.

**[00298]** In a specific embodiment, a chimeric influenza hemagglutinin polypeptide that is part of a live virus vaccine is found and/or expressed on the surface of the live virus (*e.g.*, the surface of the live influenza virus).

**[00299]** In a specific embodiment, a live virus vaccine provided herein does not comprise a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide comprising the globular head domain of A/Vietnam/1203/2004 (H5). In another specific embodiment, a live virus vaccine provided herein does not comprise a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide comprising the stem domain of A/Perth/16/2009 (H3).

**[00300]** In a specific embodiment, a live virus vaccine provided herein does not comprise a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide comprising the globular head domain of A/mallard/Alberta/24/2001 (H7). In another specific embodiment, a live virus vaccine provided herein does not comprise a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide comprising the stem domain of A/Perth/16/2009 (H3).

### 5.10.3 Inactivated Virus Vaccines

**[00301]** In one embodiment, provided herein are immunogenic compositions (*e.g.*, vaccines) comprising an inactivated virus containing a chimeric influenza hemagglutinin (HA) polypeptide described herein. In specific embodiments, the chimeric influenza hemagglutinin (HA) polypeptide is membrane-bound. In particular embodiments, the inactivated virus is an influenza virus, such as described in Section 5.4, *supra*. In other embodiments, the inactivated virus is a non-influenza virus, such as described in Section 5.5, *supra*. In some embodiments, an immunogenic composition comprises two, three, four or more inactivated viruses containing two, three, four or more different chimeric influenza hemagglutinin (HA) polypeptides described herein. In certain embodiments, the inactivated virus immunogenic compositions comprise one or more adjuvants.

**[00302]** Techniques known to one of skill in the art may be used to inactivate viruses containing a chimeric influenza hemagglutinin (HA) polypeptide described herein. Common methods use formalin, heat, or detergent for inactivation. *See*, *e.g.*, U.S. Patent No. 6,635,246,

which is herein incorporated by reference in its entirety. Other methods include those described in U.S. Patent Nos. 5,891,705; 5,106,619 and 4,693,981, which are incorporated herein by reference in their entireties.

**[00303]** In certain embodiments, provided herein are immunogenic compositions (*e.g.*, vaccines) comprising inactivated influenza virus such that each dose of the immunogenic composition comprises about 7.5 μg to about 90 μg, or about 15 to about 60 μg, of a chimeric influenza hemagglutinin (HA) polypeptide described herein, about 1.0 to about 5.0 mg sodium chloride, about 20 to about 100 μg monobasic sodium phosphate, about 100 to about 500 μg dibasic sodium phosphate, about 5 to about 30 μg monobasic potassium phosphate, about 5 to about 30 μg potassium chloride, and about .5 to about 3.0 μg calcium chloride. In some embodiments, the immunogenic compositions (*e.g.*, vaccines) are packaged as single 0.25 ml or single 0.5 ml doses. In other embodiments, the immunogenic compositions (*e.g.*, vaccines) are packaged as multi-dose formulations.

**[00304]** In certain embodiments, provided herein are immunogenic compositions (*e.g.*, vaccines) comprising inactivated influenza virus such that each dose of the immunogenic composition comprises about 7.5 μg to about 90 μg, or about 15 to about 60 μg, of a chimeric influenza hemagglutinin (HA) polypeptide described herein, about 0.001% to 0.01% thimerosal, about 1.0 to about 5.0 mg sodium chloride, about 20 to about 100 μg monobasic sodium phosphate, about 100 to about 500 μg dibasic sodium phosphate, about 5 to about 30 μg monobasic potassium phosphate, about 5 to about 30 μg potassium chloride, and about 0.5 to about 3.0 μg calcium chloride per dose. In some embodiments, the immunogenic compositions (*e.g.*, vaccines) are packaged as single 0.25 ml or single 0.5 ml doses. In other embodiments, the immunogenic compositions (*e.g.*, vaccines) are packaged as multi-dose formulations.

**[00305]** In a specific embodiment, immunogenic compositions (*e.g.*, vaccines) provided herein are packaged as single 0.25 ml doses and comprise 22.5 μg of a chimeric influenza hemagglutinin (HA) polypeptide described herein, 2.05 mg sodium chloride, 40 μg monobasic sodium phosphate, 150 μg dibasic sodium phosphate, 10 μg monobasic potassium phosphate, 10 μg potassium chloride, and 0.75 μg calcium chloride per dose.

**[00306]** In a specific embodiment, immunogenic compositions (*e.g.*, vaccines) provided herein are packaged as single 0.5 ml doses and comprise 45 μg of a chimeric influenza hemagglutinin (HA) polypeptide described herein, 4.1 mg sodium chloride, 80 μg monobasic

sodium phosphate, 300 μg dibasic sodium phosphate, 20 μg monobasic potassium phosphate, 20 μg potassium chloride, and 1.5 μg calcium chloride per dose.

**[00307]** In a specific embodiment, immunogenic compositions (*e.g.*, vaccines) are packaged as multi-dose formulations comprising or consisting of 5.0 ml of vaccine (0.5 ml per dose) and comprise 24.5 μg of mercury (from thimerosal), 45 μg of a chimeric influenza hemagglutinin (HA) polypeptide described herein, 4.1 mg sodium chloride, 80 μg monobasic sodium phosphate, 300 μg dibasic sodium phosphate, 20 μg monobasic potassium phosphate, 20 μg potassium chloride, and 1.5 μg calcium chloride per dose.

**[00308]** In a specific embodiment, the inactivated virus that contains a chimeric influenza hemagglutinin (HA) polypeptide described herein is propagated in embryonated chicken eggs before its inactivation and subsequent use in an immunogenic composition described herein. In another specific embodiment, the inactivated virus that contains a chimeric influenza hemagglutinin (HA) polypeptide described herein is not propagated in embryonated chicken eggs before its inactivation and subsequent use in an immunogenic composition described herein. In another specific embodiment, the inactivated virus that contains a chimeric influenza hemagglutinin (HA) polypeptide described herein is propagated in mammalian cells, e.g., immortalized human cells (see, e.g., International Application No. PCT/EP2006/067566 published as International Publication No. WO 07/045674 which is herein incorporated by reference in its entirety), canine kidney cells such as MDCK cells (see, e.g., International Application No. PCT/IB2007/003536 published as International Publication No. WO 08/032219 which is herein incorporated by reference in its entirety), Vero cells, PerC.6 cells, or duck cells such as EB66 cells before its inactivation and subsequent use in an immunogenic composition described herein.

**[00309]** In a specific embodiment, provided herein is a monovalent inactivated virus vaccine comprising a chimeric influenza hemagglutinin (HA) polypeptide described herein. In a specific embodiment, provided herein is a monovalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide (e.g., a cH5/1 chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide (e.g., a cH5/3 chimeric influenza hemagglutinin

polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide (e.g., a cH7/3 chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide (e.g., a cH5/B chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide (e.g., a cH7/1 chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide (e.g., a B/B chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH4/3 chimeric influenza hemagglutinin polypeptide (e.g., a cH4/3 chimeric influenza hemagglutinin polypeptide described in Section 5.1).

**[00310]** In specific embodiments, provided herein are bivalent inactivated virus vaccines comprising viruses that contain and/or comprise a genome that encodes a chimeric influenza hemagglutinin (HA) polypeptide described herein. In certain embodiments, provided herein is a bivalent inactivated virus vaccine comprising two chimeric influenza hemagglutinin polypeptides, wherein the two chimeric influenza hemagglutinin polypeptides comprise the same influenza hemagglutinin globular head domain from an influenza virus and each of the two chimeric influenza hemagglutinin polypeptides comprises a different influenza hemagglutinin stem domain from two different influenza viruses. In certain embodiments, the influenza hemagglutinin stem domains are from two different influenza strains, subtypes, or groups. In a specific embodiment, provided herein is a bivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome

that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide.

**[00311]** In another specific embodiment, provided herein is a bivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide.

**[00312]** In another specific embodiment, provided herein is a bivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/3

chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide.

**[00313]** In another specific embodiment, provided herein is a bivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide.

**[00314]** In another specific embodiment, provided herein is a bivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH4/3 chimeric influenza hemagglutinin polypeptide.

**[00315]** In specific embodiments, provided herein are trivalent inactivated virus vaccines comprising viruses that contain and/or comprise a genome that encodes a chimeric influenza hemagglutinin (HA) polypeptide described herein. In certain embodiments, provided herein is a trivalent inactivated virus vaccine comprising three chimeric influenza hemagglutinin polypeptides, wherein the three chimeric influenza hemagglutinin polypeptides comprise the same influenza hemagglutinin globular head domain from an influenza virus and each of the three chimeric influenza hemagglutinin polypeptides comprise a different influenza

hemagglutinin stem domain from three different influenza viruses. In certain embodiments, the influenza hemagglutinin stem domains are from three different influenza virus strains, subtypes, or groups. In a specific embodiment, provided herein is a trivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide.

**[00316]** In another specific embodiment, provided herein is a trivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises

a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent inactivated virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH4/3 chimeric influenza hemagglutinin polypeptide

**[00317]** In a specific embodiment, a chimeric influenza hemagglutinin polypeptide that is part of an inactivated virus vaccine is found and/or expressed on the surface of the inactivated virus (*e.g.*, the surface of an inactivated influenza virus).

**[00318]** In a specific embodiment, an inactivated virus vaccine provided herein does not comprise a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide comprising the globular head domain of A/Vietnam/1203/2004 (H5). In another specific embodiment, an inactivated virus vaccine provided herein does not comprise a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide comprising the stem domain of A/Perth/16/2009 (H3).

**[00319]** In a specific embodiment, an inactivated virus vaccine provided herein does not comprise a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide comprising the globular head domain of A/mallard/Alberta/24/2001 (H7). In another specific embodiment, an inactivated virus vaccine provided herein does not comprise a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide comprising the stem domain of A/Perth/16/2009 (H3).

### 5.10.4 Split Virus Vaccines

**[00320]** In one embodiment, an immunogenic composition comprising a chimeric influenza hemagglutinin (HA) polypeptide described herein is a split virus vaccine. In some embodiments, split virus vaccine contains two, three, four or more different chimeric influenza hemagglutinin (HA) polypeptides described herein. In certain embodiments, the chimeric influenza hemagglutinin (HA) polypeptide is/was membrane-bound. In certain embodiments, the split virus vaccines comprise one or more adjuvants.

**[00321]** Techniques for producing split virus vaccines are known to those skilled in the art. By way of non-limiting example, an influenza virus split vaccine may be prepared using inactivated particles disrupted with detergents. One example of a split virus vaccine that can be

adapted for use in accordance with the methods described herein is the fluzone®, Influenza Virus Vaccine (Zonal Purified, Subvirion) for intramuscular use, which is formulated as a sterile suspension prepared from influenza viruses propagated in embryonated chicken eggs. The virus-containing fluids are harvested and inactivated with formaldehyde. Influenza virus is concentrated and purified in a linear sucrose density gradient solution using a continuous flow centrifuge. The virus is then chemically disrupted using a nonionic surfactant, octoxinol-9, (Triton® X-100 - A registered trademark of Union Carbide, Co.) producing a "split virus." The split virus is then further purified by chemical means and suspended in sodium phosphate-buffered isotonic sodium chloride solution.

**[00322]** In certain embodiments, provided herein are split virus vaccines comprising about about 7.5 μg to about 90 μg, or 10 μg to about 60 μg, of one or more chimeric influenza hemagglutinin (HA) polypeptide described herein, about 0.01 to about 1.0 mg octoxynol-10 (TRITON X-100®, about 0.5 to 0.5 mg α-tocopheryl hydrogen succinate, about 0.1 to 1.0 mg polysorbate 80 (Tween 80), about 0.001 to about 0.003 μg hydrocortisone, about 0.05 to about 0.3 μg gentamcin sulfate, about 0.5 to about 2.0 μgchicken egg protein (ovalbumin), about 25 to 75 μg formaldehyde, and about 25 to 75 μg sodium deoxycholate.

**[00323]** In a specific embodiment, a split virus vaccine provided herein comprises or consists of a 0.5 ml dose that comprises 45 μg of a chimeric influenza hemagglutinin (HA) polypeptide described herein, ≤ 0.085 mg octoxynol-10 (TRITON X-100®, ≤ 0.1 mg α-tocopheryl hydrogen succinate, ≤ .415 mg polysorbate 80 (Tween 80), ≤ 0.0016 μg hydrocortisone, ≤ 0.15 μg gentamcin sulfate, ≤ 1.0 chicken egg protein (ovalbumin), ≤ 50 μg formaldehyde, and ≤ 50 μg sodium deoxycholate. In some embodiments, the 0.5 ml dose subunit vaccine is packaged in a pre-filled syringe.

**[00324]** In a specific embodiment, the split virus vaccine is prepared using influenza virus that was propagated in embryonated chicken eggs. In another specific embodiment, the split virus vaccine is prepared using influenza virus that was not propagated in embryonated chicken eggs. In another specific embodiment, the split virus vaccine is prepared using influenza virus that was propagated in mammalian cells, e.g., immortalized human cells (see, e.g., PCT/EP2006/067566 published as WO 07/045674 which is herein incorporated by reference in its entirety), canine kidney cells such as MDCK cells (see, e.g., PCT/IB2007/003536 published as WO 08/032219

which is herein incorporated by reference in its entirety), Vero cells, PerC.6 cells, or duck cells such as EB66 cells.

**[00325]** In a specific embodiment, provided herein is a monovalent split virus vaccine comprising a chimeric influenza hemagglutinin (HA) polypeptide described herein. In a specific embodiment, provided herein is a monovalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide (e.g., a cH5/1 chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide (e.g., a cH5/3 chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide (e.g., a cH7/3 chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide (e.g., a cH5/B chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide (e.g., a cH7/1 chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide (e.g., a B/B chimeric influenza hemagglutinin polypeptide described in Section 5.1). In another specific embodiment, provided herein is a monovalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH4/3 chimeric influenza hemagglutinin polypeptide (e.g., a cH4/3 chimeric influenza hemagglutinin polypeptide described in Section 5.1).

**[00326]** In specific embodiments, provided herein are bivalent split virus vaccines comprising viruses that contain and/or comprise a genome that encodes a chimeric influenza hemagglutinin (HA) polypeptide described herein. In certain embodiments, provided herein is a bivalent split virus vaccine comprising two chimeric influenza hemagglutinin polypeptides, wherein the two

chimeric influenza hemagglutinin polypeptides comprise the same influenza hemagglutinin globular head domain from an influenza virus and each of the two chimeric influenza hemagglutinin polypeptides comprises a different influenza hemagglutinin stem domain from two different influenza viruses. In certain embodiments, the influenza hemagglutinin stem domains are from two different influenza strains, subtypes, or groups. In a specific embodiment, provided herein is a bivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide.

**[00327]** In another specific embodiment, provided herein is a bivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent split

virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide.

**[00328]** In another specific embodiment, provided herein is a bivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide.

**[00329]** In another specific embodiment, provided herein is a bivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a bivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide.

**[00330]** In another specific embodiment, provided herein is a bivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment,

provided herein is a bivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH4/3 chimeric influenza hemagglutinin polypeptide.

**[00331]** In specific embodiments, provided herein are trivalent split virus vaccines comprising viruses that contain and/or comprise a genome that encodes a chimeric influenza hemagglutinin (HA) polypeptide described herein. In certain embodiments, provided herein is a trivalent split virus vaccine comprising three chimeric influenza hemagglutinin polypeptides, wherein the three chimeric influenza hemagglutinin polypeptides comprise the same influenza hemagglutinin globular head domain from an influenza virus and each of the three chimeric influenza hemagglutinin polypeptides comprise a different influenza hemagglutinin stem domain from three different influenza viruses. In certain embodiments, the influenza hemagglutinin stem domains are from three different influenza virus strains, subtypes, or groups. In a specific embodiment, provided herein is a trivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide.

**[00332]** In another specific embodiment, provided herein is a trivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cH5/B chimeric influenza hemagglutinin polypeptide. In

another specific embodiment, provided herein is a trivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cH7/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH5/1 chimeric influenza hemagglutinin polypeptide, a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide, and a virus that contains and/or comprises a genome that encodes a cB/B chimeric influenza hemagglutinin polypeptide. In another specific embodiment, provided herein is a trivalent split virus vaccine comprising a virus that contains and/or comprises a genome that encodes a cH4/3 chimeric influenza hemagglutinin polypeptide.

**[00333]** In a specific embodiment, a split virus vaccine provided herein does not comprise a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide comprising the globular head domain of A/Vietnam/1203/2004 (H5). In another specific embodiment, a split virus vaccine provided herein does not comprise a virus that contains and/or comprises a genome that encodes a cH5/3 chimeric influenza hemagglutinin polypeptide comprising the stem domain of A/Perth/16/2009 (H3).

**[00334]** In a specific embodiment, a split virus vaccine provided herein does not comprise a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide comprising the globular head domain of A/mallard/Alberta/24/2001 (H7). In another specific embodiment, a split virus vaccine provided herein does not comprise a virus that contains and/or comprises a genome that encodes a cH7/3 chimeric influenza hemagglutinin polypeptide comprising the stem domain of A/Perth/16/2009 (H3).

### 5.10.5 Adjuvants

**[00335]** In certain embodiments, the compositions described herein comprise, or are administered in combination with, an adjuvant. The adjuvant for administration in combination with a composition described herein may be administered before, concommitantly with, or after administration of said composition. In some embodiments, the term "adjuvant" refers to a compound that when administered in conjunction with or as part of a composition described herein augments, enhances and/or boosts the immune response to a chimeric influenza

hemagglutinin (HA) polypeptide described herein, but when the compound is administered alone does not generate an immune response to the polypeptide. In some embodiments, the adjuvant generates an immune response to the polypeptide and does not produce an allergy or other adverse reaction. Adjuvants can enhance an immune response by several mechanisms including, *e.g.*, lymphocyte recruitment, stimulation of B and/or T cells, and stimulation of macrophages.

**[00336]** In certain embodiments, an adjuvant augments the intrinsic response to chimeric influenza hemagglutinin (HA) polypeptide without causing conformational changes in the polypeptide that affect the qualitative form of the response. Specific examples of adjuvants include, but are not limited to, aluminum salts (alum) (such as aluminum hydroxide, aluminum phosphate, and aluminum sulfate), 3 De-O-acylated monophosphoryl lipid A (MPL) (see GB 2220211), MF59 (Novartis), AS03 (GlaxoSmithKline), AS04 (GlaxoSmithKline), polysorbate 80 (Tween 80; ICL Americas, Inc.), imidazopyridine compounds (see International Application No. PCT/US2007/064857, published as International Publication No. WO2007/109812), imidazoquinoxaline compounds (see International Application No. PCT/US2007/064858, published as International Publication No. WO2007/109813), Matrix-M (iscanova), MVA (the Jenner Institute, Oxford), ISCOMATRIX (CSL Behring), AddaVax (Invivogen), polyI:C (Invivogen), *in vitro* transcribed RNA hairpin from Sendai virus Cantell strain defective interfering RNA, and saponins, such as QS21 (see Kensil *et al.*, in Vaccine Design: The Subunit and Adjuvant Approach (eds. Powell & Newman, Plenum Press, NY, 1995); U.S. Pat. No. 5,057,540). In some embodiments, the adjuvant is Freund's adjuvant (complete or incomplete). Other adjuvants are oil in water emulsions (such as squalene or peanut oil), optionally in combination with immune stimulants, such as monophosphoryl lipid A (see Stoute *et al.*, N. Engl. J. Med. 336, 86-91 (1997)). Another adjuvant is CpG (Bioworld Today, Nov. 15, 1998). Such adjuvants can be used with or without other specific immunostimulating agents such as MPL or 3-DMP, QS21, polymeric or monomeric amino acids such as polyglutamic acid or polylysine, or other immunopotentiating agents described in Section 5.4, *supra*. In another embodiment, the adjuvant is a physical adjuvant, such as microneedles and microneedle patches. In another embodiment, the adjuvant is a Toll-like receptor (TLR) stimulatory molecule such as flagellin (McSorley *et al.*,2002. *J. Immunol.* 169:3914-3919). It should be understood that different formulations of chimeric influenza hemagglutinin (HA) polypeptides described herein may comprise different adjuvants or may comprise the same adjuvant.

## 5.11 PROPHYLACTIC AND THERAPEUTIC USES

**[00337]** In one aspect, provided herein are methods for inducing an immune response in a subject utilizing an active compound (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or a composition (e.g., vaccine formulation) described herein. In a specific embodiment, a method for inducing an immune response to an influenza virus hemagglutinin (HA) polypeptide in a subject comprises administering to a subject in need thereof an effective amount of a chimeric influenza hemagglutinin (HA) polypeptide described herein or an immunogenic composition thereof (e.g., a vaccine formulation thereof). In another embodiment, a method for inducing an immune response to an influenza virus hemagglutinin polypeptide in a subject comprises administering to a subject in need thereof an effective amount of a nucleic acid encoding a chimeric influenza hemagglutinin (HA) polypeptide described herein or an immunogenic composition thereof. In another embodiment, a method for inducing an immune response to an influenza virus hemagglutinin polypeptide in a subject comprises administering to a subject in need thereof an effective amount of a viral vector containing or expressing a chimeric influenza hemagglutinin (HA) polypeptide described herein or an immunogenic composition thereof. In yet another embodiment, a method for inducing an immune response to an influenza virus hemagglutinin polypeptide in a subject comprises administering to a subject in need thereof an effective amount of cells stimulated with a chimeric influenza hemagglutinin (HA) polypeptide described herein or a pharmaceutical composition thereof. In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide described herein used in the method is a purified chimeric influenza hemagglutinin (HA) polypeptide described herein derived from a mammalian cell, a plant cell, or an insect cell.

**[00338]** In a specific embodiment, a method for inducing an immune response to an influenza virus hemagglutinin polypeptide in a subject comprises administering to a subject in need thereof a subunit vaccine described herein (see Section 5.10.1). In another embodiment, a method for inducing an immune response to an influenza virus hemagglutinin polypeptide in a subject comprises administering to a subject in need thereof a live virus vaccine described herein (see Section 5.10.2). In particular embodiments, the live virus vaccine comprises an attenuated virus. In another embodiment, a method for inducing an immune response to an influenza virus

hemagglutinin polypeptide in a subject comprises administering to a subject in need thereof an inactivated virus vaccine described herein (see Section 5.10.3). In another embodiment, a method for inducing an immune response to an influenza virus hemagglutinin polypeptide in a subject comprises administering to a subject in need thereof a split virus vaccine described herein (see Section 5.10.4). In another embodiment, a method for inducing an immune response to an influenza virus hemagglutinin polypeptide in a subject comprises administering to a subject in need thereof a virus-like particle vaccine described herein (see Section 5.6). In another embodiment, a method for inducing an immune response to an influenza hemagglutinin polypeptide comprises administering to a subject in need thereof a virosome described herein (see Section 5.6). In another embodiment, a method for inducing an immune response to an influenza hemagglutinin polypeptide comprises administering to a subject in need thereof a bacteria expressing or engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein or a composition thereof (see Section 5.7). In certain embodiments, a chimeric influenza hemagglutinin (HA) polypeptide described herein used in the method is a purified chimeric influenza hemagglutinin (HA) polypeptide described herein derived from a mammalian cell, a plant cell, or an insect cell.

**[00339]** In some embodiments, the immune response induced by an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or a composition (e.g., vaccine formulation) described herein is effective to prevent and/or treat an influenza virus infection caused by any subtype or strain of influenza virus. In some embodiments, the immune response induced by an active compound or a composition (e.g., vaccine formulation) described herein is effective to prevent and/or treat an influenza virus infection caused by one or more strains within the same subtype of influenza virus. In some embodiments, the immune response induced by an active compound or a composition (e.g., vaccine formulation) described herein is effective to prevent and/or treat an influenza virus infection caused by multiple strains of the same subtype of influenza virus.

**[00340]** In some embodiments, the immune response induced by an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a

polypeptide, cells stimulated with such a polypeptide) or a composition (e.g., vaccine formulation) described herein is effective to prevent and/or treat an influenza virus infection caused by (i) H1N1 and H1N2 subtypes; (ii) H1N1 and H3N1 subtypes; (iii) H1N2 and H3N2 subtypes; and/or (iv) any of the combinations of (i)-(iii) and influenza B.

**[00341]** In certain embodiments, the immune response induced by an active compound or a composition (e.g., vaccine formulation) described herein is effective to prevent and/or treat an influenza virus infection caused by a subtype of influenza virus that belongs to one HA group (e.g., Group 1, which comprises H1, H2, H5, H6, H8, H9, H11, H12, H13, H16, H17, and H18) and not the other HA group (e.g., Group 2, which comprises H3, H4, H7, H10, H14, and H15). For example, the immune response induced may be effective to prevent and/or treat an influenza virus infection caused by an influenza virus that belongs to the HA group consisting of H11, H13, H16, H9, H8, H12, H6, H1, H5 and/or H2. Alternatively, the immune response induced may be effective to prevent and/or treat an influenza virus infection caused by an influenza virus that belongs to the HA group consisting of H3, H4, H14, H10, H15 and/or H7. In some embodiments, the immune response induced by an active compound or a composition (e.g., vaccine formulation) described herein is effective to prevent and/or treat an influenza virus infection caused by one, two, three, four or five subtypes of influenza virus. In certain embodiments, the immune response induced by an active compound or a composition (e.g., vaccine formulation) described herein is effective to prevent and/or treat an influenza virus infection caused by six, seven, eight, nine, ten, eleven, twelve, thirteen, fourteen or fifteen subtypes of influenza virus. In a specific embodiment, the immune response induced by an active compound or a composition (e.g., vaccine formulation) described herein is effective to prevent and/or treat an influenza virus infection caused by one, two, or more strains of an influenza virus that belongs to the H1 HA group and/or one, two, or more strains of an influenza virus that belongs to the H2 HA group. In another specific embodiment, the immune response induced by an active compound or a composition (e.g., vaccine formulation) described herein is effective to prevent and/or treat an influenza virus infection caused by one, two, or more strains of an influenza virus that belongs to the H1 HA group; one, two, or more strains of an influenza virus that belongs to the H3 HA group; and/or one, two, or more influenza B virus strains.

**[00342]** In some embodiments, the immune response induced by an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding

such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or a composition (e.g., vaccine formulation) described herein is effective to prevent and/or treat an influenza virus infection caused by both H1N1 and H2N2 subtypes. In other embodiments, the immune response induced by an active compound or a composition (e.g., vaccine formulation) described herein is not effective to prevent and/or treat an influenza virus infection caused by both H1N1 and H2N2 subtypes. In some embodiments, the immune response induced by an active compound or a composition (e.g., vaccine formulation) described herein is effective to prevent and/or treat an influenza virus infection caused by H1N1, H2N2, and H3N2 subtypes. In some embodiments, the immune response induced by an active compound or a composition (e.g., vaccine formulation) described herein is effective to prevent and/or treat an influenza virus infection caused by H3N2 subtypes. In other embodiments, the immune response induced by an active compound or a composition (e.g., vaccine formulation) described herein is not effective to prevent and/or treat an influenza virus infection caused by H3N2 subtypes.

**[00343]** In certain embodiments, the immune response induced by an active compound or a composition (e.g., vaccine formulation) described herein is effective to prevent and/or treat an influenza virus disease caused by a subtype of influenza virus that belongs to one HA group and not the other HA group. For example, the immune response induced may be effective to prevent and/or treat an influenza virus disease caused by an influenza virus that belongs to the HA group consisting of H11, H13, H16, H9, H8, H12, H6, H1, H5 and/or H2. Alternatively, the immune response induced may be effective to prevent and/or treat an influenza virus disease caused by an influenza virus that belongs to the HA group consisting of H3, H4, H14, H10, H15 and/or H7. In some embodiments, the immune response induced by an active compound or a composition (e.g., vaccine formulation) described herein is effective to prevent and/or treat an influenza virus disease caused by any of one, two, three, four or five subtypes of influenza virus. In certain embodiments, the immune response induced by an active compound or a composition (e.g., vaccine formulation) described herein is effective to prevent and/or treat an influenza virus disease caused by any of six, seven, eight, nine, ten, eleven, twelve, thirteen, fourteen or fifteen subtypes of influenza virus. In some embodiments, the immune response induced by an active compound or a composition (e.g., vaccine formulation) described herein is effective to prevent

and/or treat an influenza virus disease caused by one or more strains within the same subtype of influenza virus.

**[00344]** In some embodiments, the immune response induced by an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or a composition (e.g., vaccine formulation) described herein is effective to reduce symptoms resulting from an influenza virus disease/infection. Symptoms of influenza virus disease/infection include, but are not limited to, body aches (especially joints and throat), fever, nausea, headaches, irritated eyes, fatigue, sore throat, reddened eyes or skin, and abdominal pain.

**[00345]** In some embodiments, the immune response induced by an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or a composition (e.g., vaccine formulation) described herein is effective to reduce the hospitalization of a subject suffering from an influenza virus disease/infection. In some embodiments, the immune response induced by an active compound or a composition (e.g., vaccine formulation) described herein is effective to reduce the duration of hospitalization of a subject suffering from an influenza virus disease/infection.

**[00346]** In another aspect, provided herein are methods for preventing and/or treating an influenza virus infection in a subject utilizing an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or a composition (e.g., vaccine formulation) described herein. In one embodiment, a method for preventing or treating an influenza virus infection in a subject comprises administering to a subject in need thereof a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector containing or expressing such a polypeptide, or a composition of any one of the foregoing. In a specific embodiment, a method for preventing or treating an influenza virus infection in a subject comprises administering to a subject in need thereof a subunit vaccine, a live virus vaccine, an inactivated virus vaccine, a split virus vaccine or a virus-like particle vaccine described herein.

**[00347]** In another aspect, provided herein are methods for preventing and/or treating an influenza virus disease in a subject utilizing a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector containing or expressing such a polypeptide, or cells stimulated with such a polypeptide, or a composition (e.g., vaccine formulation) described herein. In a specific embodiment, a method for preventing or treating an influenza virus disease in a subject comprises administering to a subject in need thereof an effective amount of a chimeric influenza hemagglutinin (HA) polypeptide described herein or an immunogenic composition thereof. In another embodiment, a method for preventing or treating an influenza virus disease in a subject comprises administering to a subject in need thereof an effective amount of a nucleic acid encoding a chimeric influenza hemagglutinin (HA) polypeptide described herein or an immunogenic composition thereof. In another embodiment, a method for preventing or treating an influenza virus disease in a subject comprises administering to a subject in need thereof an effective amount of a viral vector containing or expressing a chimeric influenza hemagglutinin (HA) polypeptide described herein or an immunogenic composition thereof. In yet another embodiment, a method for preventing or treating an influenza virus disease in a subject comprises administering to a subject in need thereof an effective amount of cells stimulated with a chimeric influenza hemagglutinin (HA) polypeptide described herein or a pharmaceutical composition thereof.

**[00348]** In a specific embodiment, a method for preventing or treating an influenza virus disease in a subject comprises administering to a subject in need thereof a subunit vaccine described herein. In another embodiment, a method for preventing or treating an influenza virus disease in a subject comprises administering to a subject in need thereof a live virus vaccine described herein. In particular embodiments, the live virus vaccine comprises an attenuated virus. In another embodiment, a method for preventing or treating an influenza virus disease in a subject comprises administering to a subject in need thereof an inactivated virus vaccine described herein. In another embodiment, a method for preventing or treating an influenza virus disease in a subject comprises administering to a subject in need thereof a split virus vaccine described herein. In another embodiment, a method for preventing or treating an influenza virus disease comprises administering to a subject in need thereof a virus-like particle vaccine described herein. In another embodiment, a method for preventing or treating an influenza virus disease in a subject, comprising administering to a subject in need thereof a virosome described

herein. In another embodiment, a method for preventing or treating an influenza virus disease in a subject comprising administering to a subject in need thereof a bacteria expressing or engineered to express a chimeric influenza hemagglutinin (HA) polypeptide described herein or a composition thereof.

**[00349]** In a specific embodiment, a method for preventing or treating an influenza virus disease in a subject comprises administering a multivalent vaccine (*e.g.*, a bivalent or trivalent vaccine) to a subject thereof, wherein the multivalent vaccine comprises two or more chimeric influenza hemagglutinin polypeptides. In certain embodiments, a second, multivalent vaccine (*e.g.*, a bivalent or trivalent vaccine) is administered to the subject as a booster, wherein the second multivalent vaccine comprises two or more chimeric influenza hemagglutinin polypeptides, and wherein the second multivalent vaccine is different than the first multivalent vaccine In a specific embodiment, the chimeric influenza hemagglutinin polypeptides of the second multivalent vaccine differ from the chimeric influenza hemagglutinin polyepptides of the first multivalent vaccine with respect to the hemagglutinin globular head domains of the chimeric influenza hemagglutinin polypeptides. In certain embodiments, the hemagglutinin stem domains of the chimeric influenza hemagglutinin polypeptides of the second multivalent vaccine are the same as the hemagglutinin stem domains of the chimeric influenza hemagglutinin polypeptides of the first multivalent vaccine.

**[00350]** In another aspect, provided herein are methods of preventing and/or treating an influenza virus disease in a subject by administering neutralizing antibodies described herein (see Section 5.9). In a specific embodiment, a method for preventing or treating an influenza virus disease in a subject comprises administering to a subject in need thereof an effective amount of a neutralizing antibody described herein, or a pharmaceutical composition thereof. In particular embodiments, the neutralizing antibody is a monoclonal antibody. In certain embodiments, the neutralizing antibody is not CR8114, CR8020 (Ekiert *et al.,* 2011. *Science*. 333(6044): 843-850), FI6 (Corti *et al.,* 2011. *Science*. 333(6044) 850-856, DOI: 10.1126/science.1205669), the influenza B virus stalk mAbs 3A2, 10C4, or 5A7 (Yasugi *et al.,* 2013. *PLoS Pathog.* 9(2): e1003150), CR6261, CR6325, CR6329, CR6307, CR6323, 2A, D7, D8, F10, G17, H40, A66, D80, E88, E90, H98, C179 (FERM BP-4517), AI3C (FERM BP-4516) or any other antibody described in Ekiert DC *et al.* (2009) Antibody Recognition of a Highly Conserved Influenza Virus Epitope. Science (published in Science Express February 26, 2009); Kashyap *et al.* (2008)

Combinatorial antibody libraries from survivors of the Turkish H5N1 avian influenza outbreak reveal virus neutralization strategies. Proc Natl Acad Sci U S A 105: 5986-5991; Sui *et al.* (2009) Structural and functional bases for broad-spectrum neutralization of avian and human influenza A viruses. Nat Struct Mol Biol 16: 265-273; U.S. Patent Nos. 5,589,174, 5,631,350, 6,337,070, and 6,720,409; International Application No. PCT/US2007/068983 published as International Publication No. WO 2007/134237; International Application No. PCT/US2008/075998 published as International Publication No. WO 2009/036157; International Application No. PCT/EP2007/059356 published as International Publication No. WO 2008/028946; and International Application No. PCT/US2008/085876 published as International Publication No. WO 2009/079259. In other embodiments, the neutralizing antibody is not an antibody described in Wang *et al.* (2010) "Broadly Protective Monoclonal Antibodies against H3 Influenza Viruses following Sequential Immunization with Different Hemagglutinins," PLOS Pathogens 6(2):1-9.

**[00351]** In certain embodiments, the methods for preventing or treating an influenza virus disease or infection in a subject (e.g., a human or non-human animal) provided herein result in a reduction in the replication of the influenza virus in the subject as measured by *in vivo* and *in vitro* assays known to those of skill in the art and described herein. In some embodiments, the replication of the influenza virus is reduced by approximately 1 log or more, approximately 2 logs or more, approximately 3 logs or more, approximately 4 logs or more, approximately 5 logs or more, approximately 6 logs or more, approximately 7 logs or more, approximately 8 logs or more, approximately 9 logs or more, approximately 10 logs or more, 1 to 3 logs, 1 to 5 logs, 1 to 8 logs, 1 to 9 logs, 2 to 10 logs, 2 to 5 logs, 2 to 7 logs, 2 logs to 8 logs, 2 to 9 logs, 2 to 10 logs 3 to 5 logs, 3 to 7 logs, 3 to 8 logs, 3 to 9 logs, 4 to 6 logs, 4 to 8 logs, 4 to 9 logs, 5 to 6 logs, 5 to 7 logs, 5 to 8 logs, 5 to 9 logs, 6 to 7 logs, 6 to 8 logs, 6 to 9 logs, 7 to 8 logs, 7 to 9 logs, or 8 to 9 logs.

### 5.11.1 Combination therapies

**[00352]** In various embodiments, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide, or a neutralizing antibody may be administered to a subject in combination with one or more other therapies (*e.g.*, antiviral, antibacterial, or immunomodulatory therapies). In some

embodiments, a pharmaceutical composition (*e.g.*, an immunogenic composition) described herein may be administered to a subject in combination with one or more therapies. The one or more other therapies may be beneficial in the treatment or prevention of an influenza virus disease or may ameliorate a symptom or condition associated with an influenza virus disease. In some embodiments, the one or more other therapies are pain relievers, anti-fever medications, or therapies that alleviate or assist with breathing. In certain embodiments, the therapies are administered less than 5 minutes apart, less than 30 minutes apart, 1 hour apart, at about 1 hour apart, at about 1 to about 2 hours apart, at about 2 hours to about 3 hours apart, at about 3 hours to about 4 hours apart, at about 4 hours to about 5 hours apart, at about 5 hours to about 6 hours apart, at about 6 hours to about 7 hours apart, at about 7 hours to about 8 hours apart, at about 8 hours to about 9 hours apart, at about 9 hours to about 10 hours apart, at about 10 hours to about 11 hours apart, at about 11 hours to about 12 hours apart, at about 12 hours to 18 hours apart, 18 hours to 24 hours apart, 24 hours to 36 hours apart, 36 hours to 48 hours apart, 48 hours to 52 hours apart, 52 hours to 60 hours apart, 60 hours to 72 hours apart, 72 hours to 84 hours apart, 84 hours to 96 hours apart, or 96 hours to 120 hours part. In specific embodiments, two or more therapies are administered within the same patent visit.

**[00353]** Any anti-viral agents well-known to one of skill in the art may used in combination with an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or pharmaceutical composition described herein. Non-limiting examples of anti-viral agents include proteins, polypeptides, peptides, fusion proteins antibodies, nucleic acid molecules, organic molecules, inorganic molecules, and small molecules that inhibit and/or reduce the attachment of a virus to its receptor, the internalization of a virus into a cell, the replication of a virus, or release of virus from a cell. In particular, anti-viral agents include, but are not limited to, nucleoside analogs (*e.g.*, zidovudine, acyclovir, gangcyclovir, vidarabine, idoxuridine, trifluridine, and ribavirin), foscarnet, amantadine, peramivir, rimantadine, saquinavir, indinavir, ritonavir, alpha-interferons and other interferons, AZT, zanamivir (Relenza®), and oseltamivir (Tamiflu®). Other anti-viral agents include influenza virus vaccines, *e.g.*, Fluarix® (GlaxoSmithKline), FluMist® (MedImmune Vaccines), Fluvirin® (Chiron Corporation),

Flulaval® (GlaxoSmithKline), Afluria® (CSL Biotherapies Inc.), Agriflu® (Novartis)or Fluzone® (Aventis Pasteur).

**[00354]** In specific embodiments, the anti-viral agent is an immunomodulatory agent that is specific for a viral antigen. In particular embodiments, the viral antigen is an influenza virus polypeptide other than a hemagglutinin polypeptide. In other embodiments, the viral antigen is an influenza virus hemagglutinin polypeptide.

**[00355]** Any anti-bacterial agents known to one of skill in the art may used in combination with an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or pharmaceutical composition described herein. Non-limiting examples of anti-bacterial agents include Amikacin, Amoxicillin, Amoxicillin-clavulanic acid, Amphothericin-B, Ampicillin, Ampicllin-sulbactam, Apramycin, Azithromycin, Aztreonam, Bacitracin, Benzylpenicillin, Caspofungin, Cefaclor, Cefadroxil, Cefalexin, Cefalothin, Cefazolin, Cefdinir, Cefepime, Cefixime, Cefmenoxime, Cefoperazone, Cefoperazone-sulbactam, Cefotaxime, Cefoxitin, Cefpirome, Cefpodoxime, Cefpodoxime-clavulanic acid, Cefpodoxime-sulbactam, Cefprozil, Cefquinome, Ceftazidime, Ceftibutin, Ceftiofur, Ceftobiprole, Ceftriaxon, Cefuroxime, Chloramphenicole, Florfenicole, Ciprofloxacin, Clarithromycin, Clinafloxacin, Clindamycin, Cloxacillin, Colistin, Cotrimoxazol (Trimthoprim/sulphamethoxazole), Dalbavancin, Dalfopristin/Quinopristin, Daptomycin, Dibekacin, Dicloxacillin, Doripenem, Doxycycline, Enrofloxacin, Ertapenem, Erythromycin, Flucloxacillin, Fluconazol, Flucytosin, Fosfomycin, Fusidic acid, Garenoxacin, Gatifloxacin, Gemifloxacin, Gentamicin, Imipenem, Itraconazole, Kanamycin, Ketoconazole, Levofloxacin, Lincomycin, Linezolid, Loracarbef, Mecillnam (amdinocillin), Meropenem, Metronidazole, Meziocillin, Mezlocillin-sulbactam, Minocycline, Moxifloxacin, Mupirocin, Nalidixic acid, Neomycin, Netilmicin, Nitrofurantoin, Norfloxacin, Ofloxacin, Oxacillin, Pefloxacin, Penicillin V, Piperacillin, Piperacillin-sulbactam, Piperacillin-tazobactam, Rifampicin, Roxythromycin, Sparfloxacin, Spectinomycin, Spiramycin, Streptomycin, Sulbactam, Sulfamethoxazole, Teicoplanin, Telavancin, Telithromycin, Temocillin, Tetracyklin, Ticarcillin, Ticarcillin-clavulanic acid, Tigecycline, Tobramycin, Trimethoprim, Trovafloxacin, Tylosin, Vancomycin, Virginiamycin, and Voriconazole.

**[00356]** In some embodiments, a combination therapy comprises active immunization with a chimeric influenza hemagglutinin (HA) polypeptide described herein, or one or more expression vectors described herein and passive immunization with one or more neutralizing antibodies generated and/or identified using a chimeric influenza hemagglutinin (HA) polypeptide described herein. In some embodiments, a combination therapy comprises immunization with one or more expression vectors described herein and administration of cells (*e.g.*, by adoptive transfer) stimulated with a chimeric influenza hemagglutinin (HA) polypeptide described herein.

**[00357]** In some embodiments, a combination therapy comprises administration of two or more different expression vectors described herein.

**[00358]** In some embodiments, a combination therapy comprises active immunization with an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) that induces an immune response to one, two, three, or more HA subtypes in one HA group (e.g., Group 1) in combination with an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) that induces an immune response to one, two, three, or more HA subtypes in the other HA group (e.g., Group 2).

**[00359]** In some embodiments, a combination therapy comprises active immunization with two or more chimeric influenza hemagglutinin (HA) polypeptides described herein.

### 5.11.2 Patient Populations

**[00360]** In certain embodiments, an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition described herein may be administered to a naïve subject, *i.e.*, a subject that does not have a disease caused by influenza virus infection or has not been and is not currently infected with an influenza virus infection. In one embodiment, an active compound or composition described herein is administered to a naïve subject that is at risk of acquiring an influenza virus infection. In one embodiment, an active compound or composition described herein is administered to a subject that does not have a disease caused by the specific influenza

virus, or has not been and is not infected with the specific influenza virus to which the chimeric influenza hemagglutinin (HA) polypeptide described herein induces an immune response. An active compound or composition described herein may also be administered to a subject that is and/or has been infected with the influenza virus or another type, subtype or strain of the influenza virus to which the chimeric influenza hemagglutinin (HA) polypeptide induces an immune response.

**[00361]** In certain embodiments, an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition described herein is administered to a patient who has been diagnosed with an influenza virus infection. In some embodiments, an active compound or composition described herein is administered to a patient infected with an influenza virus before symptoms manifest or symptoms become severe (*e.g.*, before the patient requires hospitalization). In some embodiments, an active compound or composition described herein is administered to a patient that is infected with or has been diagnosed with a different type of influenza virus than that of the influenza virus from which the head domain of the chimeric influenza hemagglutinin (HA) polypeptide of the active compound or composition was derived.

**[00362]** In certain embodiments, an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition described herein is administered to a patient that may be or is infected with an influenza virus that belongs to the same HA group as that of the head domain of the chimeric influenza hemagglutinin (HA) polypeptide. In certain embodiments, an active compound or composition described herein is administered to a patient that may be or is infected with an influenza virus of the same subtype as that of the head domain of the chimeric influenza hemagglutinin (HA) polypeptide.

**[00363]** In some embodiments, a subject to be administered an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition described herein is an animal. In certain embodiments, the animal is a bird. In certain embodiments, the animal is a

canine. In certain embodiments, the animal is a feline. In certain embodiments, the animal is a horse. In certain embodiments, the animal is a cow. In certain embodiments, the animal is a mammal, *e.g.*, a horse, swine, mouse, or primate, preferably a human.

**[00364]** In certain embodiments, a subject to be administered an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition described herein is a human adult. In certain embodiments, a subject to be administered an active compound or composition described herein is a human adult more than 50 years old. In certain embodiments, a subject to be administered an active compound or composition described herein is an elderly human subject.

**[00365]** In certain embodiments, a subject to be administered an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition described herein is a human child. In certain embodiments, a subject to be administered an active compound or composition described herein is a human infant. In certain embodiments, a subject to whom an active compound or composition described herein is administered is not an infant of less than 6 months old. In a specific embodiment, a subject to be administered an active compound or composition described herein is a human 2 years old or younger. In another specific embodiment, a subject to be administered an active compound or composition described herein is a human 5 years old or younger. In another specific embodiment, a subject to be administered an active compound or composition described herein is a human 1-5 years old.

**[00366]** In specific embodiments, a subject to be administered an active compound(i.e., a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition described herein is any infant or child more than 6 months of age and any adult over 50 years of age. In other embodiments, the subject is an individual who is pregnant. In another embodiment, the subject is an individual who may or will be pregnant during the influenza season (*e.g.*, generally, November to April in the Northern hemisphere). In specific embodiments, a subject to be

administered an active compound or composition described herein is a woman who has given birth 1, 2, 3, 4, 5, 6, 7, or 8 weeks earlier.

**[00367]** In some embodiments, the human subject to be administered an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition described herein is any individual at increased risk of influenza virus infection or disease resulting from influenza virus infection (*e.g.*, an immunocompromised or immunodeficient individual). In some embodiments, the human subject to be administered an active compound or composition described herein is any individual in close contact with an individual with increased risk of influenza virus infection or disease resulting from influenza virus infection (*e.g.*, immunocompromised or immunosuppressed individuals).

**[00368]** In some embodiments, the human subject to be administered an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition described herein is an individual affected by any condition that increases susceptibility to influenza virus infection or complications or disease resulting from influenza virus infection. In other embodiments, an active compound or composition described herein is administered to a subject in which an influenza virus infection has the potential to increase complications of another condition that the individual is affected by, or for which they are at risk. In particular embodiments, such conditions that increase susceptibility to influenza virus complications or for which influenza virus increases complications associated with the condition are, *e.g.*, conditions that affect the lung, such as cystic fibrosis, chronic obstructive pulmonary disease (COPD), emphysema, asthma, or bacterial infections (e.g., infections caused by *Haemophilus influenzae*, *Streptococcus pneumoniae*, *Legionella pneumophila*, and *Chlamydia trachomatus*); cardiovascular disease (e.g., congenital heart disease, congestive heart failure, and coronary artery disease); endocrine disorders (e.g., diabetes), neurological and neuron-developmental conditions (e.g., disorders of the brain, the spinal cord, the peripheral nerve, and muscle (such as cerebral palsy, epilepsy (seizure disorders), stroke, intellectual disability (e,g, mental retardation), muscular dystrophy, and spinal cord injury)).

**[00369]** In some embodiments, the human subject to be administered an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition described herein is an individual that resides in a group home, such as a nursing home. In some embodiments, the human subject to be administered an active compound or composition described herein works in, or spends a significant amount of time in, a group home, *e.g.*, a nursing home. In some embodiments, the human subject to be administered an active compound or composition described herein is a health care worker (*e.g.*, a doctor or nurse). In some embodiments, the human subject to be administered an active compound or composition described herein is a smoker. In a specific embodiment, the human subject to be administered an active compound or composition described herein is immunocompromised or immunosuppressed.

**[00370]** In addition, subjects at increased risk of developing complications from influenza who may be administered an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition described herein include: any individual who can transmit influenza viruses to those at high risk for complications, such as, *e.g.*, members of households with high-risk individuals, including households that will include infants younger than 6 months, individuals coming into contact with infants less than 6 months of age, or individuals who will come into contact with individuals who live in nursing homes or other long-term care facilities; individuals with long-term disorders of the lungs, heart, or circulation; individuals with metabolic diseases (*e.g.*, diabetes); individuals with kidney disorders; individuals with blood disorders (including anemia or sickle cell disease); individuals with weakened immune systems (including immunosuppression caused by medications, malignancies such as cancer, organ transplant, or HIV infection); children who receive long-term aspirin therapy (and therefore have a higher chance of developing Reye syndrome if infected with influenza).

**[00371]** In other embodiments, subjects for administration of an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition described herein include

healthy individuals six months of age or older, who: plan to travel to foreign countries and areas where flu outbreaks may be occurring, such, *e.g.*, as the tropics and the Southern Hemisphere from April through September; travel as a part of large organized tourist groups that may include persons from areas of the world where influenza viruses are circulating; attend school or college and reside in dormitories, or reside in institutional settings; or wish to reduce their risk of becoming ill with influenza.

**[00372]** In some embodiments, a subject for whom administration of an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition described herein is contraindicated include any individual for whom influenza vaccination is contraindicated, such as: infants younger than six months of age; and individuals who have had an anaphylactic reaction (allergic reactions that cause difficulty breathing, which is often followed by shock) to eggs, egg products, or other components used in the production of the immunogenic formulation. In certain embodiments, when administration of an active compound or composition described herein is contraindicated due to one or more components used in the production of the immunogenic formulation (e.g., due to the presence of egg or egg products), the active compound or composition may be produced in a manner that does not include the component that causes the administration of an active compound or composition to be contraindicated (e.g., the active compound or composition may be produced without the use of eggs or egg products).

**[00373]** In some embodiments, it may be advisable not to administer a live virus vaccine to one or more of the following patient populations: elderly humans; infants younger than 6 months old; pregnant individuals; infants under the age of 1 years old; children under the age of 2 years old; children under the age of 3 years old; children under the age of 4 years old; children under the age of 5 years old; adults under the age of 20 years old; adults under the age of 25 years old; adults under the age of 30 years old; adults under the age of 35 years old; adults under the age of 40 years old; adults under the age of 45 years old; adults under the age of 50 years old; elderly humans over the age of 70 years old; elderly humans over the age of 75 years old; elderly humans over the age of 80 years old; elderly humans over the age of 85 years old; elderly humans over the age of 90 years old; elderly humans over the age of 95 years old; children and adolescents (2-17 years of age) receiving aspirin or aspirin-containing medications, because of

the complications associated with aspirin and wild-type influenza virus infections in this age group; individuals with a history of asthma or other reactive airway diseases; individuals with chronic underlying medical conditions that may predispose them to severe influenza infections; individuals with a history of Guillain-Barre syndrome; individuals with acute serious illness with fever; or individuals who are moderately or severely ill. For such individuals, administration of inactivated virus vaccines, split virus vaccines, subunit vaccines, virosomes, virus-like particles or the non-viral vectors described herein may be preferred. In certain embodiments, subjects preferably administered a live virus vaccine may include healthy children and adolescents, ages 2-17 years, and healthy adults, ages 18-49.

**[00374]** In certain embodiments, an immunogenic formulation comprising a live virus vector is not given concurrently with other live-virus vaccines.

## 5.12 MODES OF ADMINISTRATION

### 5.12.1 Routes of Delivery

**[00375]** An active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition described herein may be delivered to a subject by a variety of routes. These include, but are not limited to, intranasal, intratracheal, oral, intradermal, intramuscular, intraperitoneal, transdermal, intravenous, conjunctival and subcutaneous routes. In some embodiments, a composition is formulated for topical administration, for example, for application to the skin. In specific embodiments, the route of administration is nasal, *e.g.*, as part of a nasal spray. In certain embodiments, a composition is formulated for intramuscular administration. In some embodiments, a composition is formulated for subcutaneous administration. In certain embodiments, a composition is not formulated for administration by injection. In specific embodiments for live virus vaccines, the vaccine is formulated for administration by a route other than injection.

**[00376]** In cases where the antigen is a viral vector, a virus-like particle vector, or a bacterial vector, for example, it may be preferable to introduce an immunogenic composition via the natural route of infection of the backbone virus or bacteria from which the vector was derived. Alternatively, it may be preferable to introduce a chimeric influenza hemagglutinin (HA)

polypeptide described herein via the natural route of infection of the influenza virus from which polypeptide is derived. The ability of an antigen, particularly a viral vector, to induce a vigorous secretory and cellular immune response can be used advantageously. For example, infection of the respiratory tract by a viral vector may induce a strong secretory immune response, for example in the urogenital system, with concomitant protection against an influenza virus. In addition, in a preferred embodiment it may be desirable to introduce the pharmaceutical compositions into the lungs by any suitable route. Pulmonary administration can also be employed, e.g., by use of an inhaler or nebulizer, and formulation with an aerosolizing agent for use as a spray.

**[00377]** In a specific embodiment, a subunit vaccine is administered intramuscularly. In another embodiment, a live influenza virus vaccine is administered intranasally. In another embodiment, an inactivated influenza virus vaccine, or a split influenza virus vaccine is administered intramuscularly. In another embodiment, a virus-like particle or composition thereof is administered intramuscularly.

**[00378]** In some embodiments, cells stimulated with a chimeric influenza hemagglutinin (HA) polypeptide described herein *in vitro* may be introduced (or re-introduced) into a subject using techniques known to one of skill in the art. In some embodiments, the cells can be introduced into the dermis, under the dermis, or into the peripheral blood stream. In some embodiments, the cells introduced into a subject are preferably cells derived from that subject, to avoid an adverse immune response. In other embodiments, cells also can be used that are derived from a donor host having a similar immune background. Other cells also can be used, including those designed to avoid an adverse immunogenic response.

### 5.12.2 Dosage and Frequency of Administration

**[00379]** The amount of an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition which will be effective in the treatment and/or prevention of an influenza virus infection or an influenza virus disease will depend on the nature of the disease, and can be determined by standard clinical techniques.

**[00380]** The precise dose to be employed in the formulation will also depend on the route of administration, and the seriousness of the infection or disease caused by it, and should be

decided according to the judgment of the practitioner and each subject's circumstances. For example, effective doses may also vary depending upon means of administration, target site, physiological state of the patient (including age, body weight, health), whether the patient is human or an animal, other medications administered, and whether treatment is prophylactic or therapeutic. Usually, the patient is a human but nonhuman mammals including transgenic mammals can also be treated. Treatment dosages are optimally titrated to optimize safety and efficacy.

**[00381]** In certain embodiments, an *in vitro* assay is employed to help identify optimal dosage ranges. Effective doses may be extrapolated from dose response curves derived from in vitro or animal model test systems.

**[00382]** Exemplary doses for nucleic acids encoding a chimeric influenza hemagglutinin (HA) polypeptide described herein range from about 10 ng to 1 g, 100 ng to 100 mg, 1 μg to 10 mg, or 30-300 μg nucleic acid, *e.g.*, DNA, per patient.

**[00383]** In certain embodiments, exemplary doses for a chimeric influenza hemagglutinin (HA) polypeptide described herein (e.g., as provided in split virus vaccines and subunit vaccines) range from about 0.5 μg to 1.0 μg, 1.0 μg to 2.0 μg, 2.0 μg to 5.0 μg, 5.0 μg to 10 μg, 15 μg to 25 μg, 25 μg to 50 μg, 50 μg to 100 μg, 100 μg to 500 μg, or 500 μg to 1.0 mg, of chimeric influenza hemagglutinin (HA) polypeptide per kilogram of the patient. In other embodiments, exemplary doses for a chimeric influenza hemagglutinin (HA) polypeptide described herein range from about 0.5 μg to 1.0 μg, 1.0 μg to 2.0 μg, 2.0 μg to 5.0 μg, 5.0 μg to 10 μg, 15 μg to 25 μg, 25 μg to 50 μg, 50 μg to 100 μg, 100 μg to 500 μg, 250 μg to 500 μg, 500 μg to 1.0 mg, or 750 μg to 1 mg of chimeric influenza hemagglutinin (HA) polypeptide per dose, and can be administered to a subject once, twice, three times or more than three times with intervals as often as needed.

**[00384]** Doses for infectious viral vectors may vary from 10-100, or more, virions per dose. In some embodiments, suitable dosages of a virus vector are $10^2$, 5 x $10^2$, $10^3$, 5 x $10^3$, $10^4$, 5 x $10^4$, $10^5$, 5 x $10^5$, $10^6$, 5 x $10^6$, $10^7$, 5 x $10^7$, $10^8$, 5 x $10^8$, 1 x $10^9$, 5 x $10^9$, 1 x $10^{10}$, 5 x $10^{10}$, 1 x $10^{11}$, 5 x $10^{11}$ or $10^{12}$ pfu, and can be administered to a subject once, twice, three or more times with intervals as often as needed.

**[00385]** In certain embodiments, exemplary doses for VLPs range from about 0.01 μg to about 100 mg, about 0.1 μg to about 100 mg, about 5 μg to about 100 mg, about 15 μg to about 50 mg,

about 15 μg to about 25 mg, about 15 μg to about 10 mg, about 15 μg to about 5 mg, about 15 μg to about 1 mg, about 15 μg to about 100 μg, about 15 μg to about 75 μg, about 5 μg to about 50 μg, about 10 μg to about 50 μg, about 15 μg to about 45 μg, about 20 μg to about 40 μg, or about 25 to about 35 μg per kilogram of the patient.

**[00386]** In one embodiment, an inactivated vaccine is formulated such that it contains about 5 μg to about 50 μg, about 10 μg to about 50 μg, about about 15 μg to about 100 μg, about 15 μg to about 75 μg, about 15 μg to about 50 μg, about 15 μg to about 30 μg, about 20 μg to about 50 μg, about 25 μg to about 40 μg, about 25 μg to about 35 μg of a chimeric influenza hemagglutinin (HA) polypeptide.

**[00387]** In certain embodiments, an active compound i.e., a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide, or composition is administered to a subject once as a single dose. For example, subjects (e.g., older subjects) that have previously been exposed to influenza may not require multiple administrations of an active compound described herein or composition thereof, but, rather may be sufficiently vaccinated by a single immunization with an active compound described herein or composition thereof. Alternatively, subjects (e.g., older subjects) that have previously been exposed to influenza may require multiple administrations of an active compound described herein or composition thereof, but may require less of such administrations than required by naive subjects (i.e., subjects not previously exposed to influenza) to become sufficiently vaccinated. Accordingly, in certain embodiments, naive subjects may require a first immunization (e.g., priming) with an active compound described herein or composition thereof followed by one, two, or more additional immunizations (e.g., boostings) with an active compound described herein or composition thereof.

**[00388]** In a specific embodiment, where a subject is administered more than one active compounds described herein or compositions thereof in succession (e.g., as part of an immunization regimen), the chimeric influenza hemagglutinin (HA) polypeptides of the active compounds or compositions thereof used in the successive administrations (i.e., the administrations that take place after the first administration) differ from the chimeric influenza hemagglutinin (HA) polypeptide of the active compound or composition thereof used in the first administration. In specific embodiments, the chimeric influenza hemagglutinin (HA)

polypeptides of the active compounds or compositions thereof used in the successive administrations comprise a different globular head domain than the chimeric influenza hemagglutinin (HA) polypeptide of the active compound or composition thereof used in the first administration but comprise the same HA stem domain as the chimeric influenza hemagglutinin (HA) polypeptide of the active compound or composition thereof used in the first administration but comprise the same HA stem domain. In specific embodiments, the chimeric influenza hemagglutinin (HA) polypeptides of the active compounds or compositions thereof used in the successive administrations comprise a different globular head domain and a different HA stem domain than the chimeric influenza hemagglutinin (HA) polypeptide of the active compound or composition thereof used in the first administration.

**[00389]** In certain embodiments, an active compound or composition (e.g., composition comprising an active compound) is administered to a subject as a single dose followed by a second dose 3 to 6 weeks later. In certain embodiments, an active compound or composition is administered to a subject as a single dose followed by a second dose 3 to 6 weeks later, which is followed by administration of a third dose 3 to 6 weeks later. In certain embodiments, the second and/or third administrations may utilize a different active compound or composition. In specific embodiments, the globular head domain of each chimeric influenza hemagglutinin (HA) polypeptide in the active compounds or compositions administered are different from one another, e.g., the first and second, or the first, second, and third administrations each use a different active compound or composition, wherein at least the globular head domain of the chimeric influenza hemagglutinin (HA) polypeptide in each active compound or composition administered differs. In accordance with these embodiments, booster inoculations may be administered to the subject at, e.g., 3 to 6 month, 6 to 9 month, or 6 to 12 month intervals following the second inoculation. In certain embodiments, the booster inoculations may utilize a different active compound or composition. In certain embodiments, the first (priming) administration comprises a full-length hemagglutinin or fragment thereof (or a nucleic acid encoding the same) and the second (booster) administration comprises administration of a chimeric influenza hemagglutinin (HA) polypeptide described herein (or a nucleic acid encoding the same, a VLP comprising the same, or a virus or bacteria expressing the same). In some embodiments, the administration of the same active compound or composition may be repeated and the administrations may be separated by at least 1 day, 2 days, 3 days, 5 days, 10 days, 15

days, 30 days, 45 days, 2 months, 75 days, 3 months, or at least 6 months. In certain embodiments, an active compound or composition is administered to a subject as a single dose once per year.

**[00390]** In specific embodiments for administration to children, two doses of an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition, given at least one month apart, are administered to a child. In specific embodiments for administration to adults, a single dose is given. In another embodiment, two doses of an active compound or composition, given at least one month apart, are administered to an adult. In another embodiment, a young child (six months to nine years old) may be administered an active compound or composition for the first time in two doses given one month apart. In a particular embodiment, a child who received only one dose in their first year of vaccination should receive two doses in the following year. In some embodiments, two doses administered 4 weeks apart are preferred for children 2 -8 years of age who are administered an influenza vaccine, *e.g.*, an immunogenic formulation described herein, for the first time. In certain embodiments, for children 6-35 months of age, a half dose (0.25 ml) may be preferred, in contrast to 0.5 ml which may be preferred for subjects over three years of age.

**[00391]** In a specific embodiment, for administration to human infants, two doses of a chimeric influenza hemagglutinin (HA) polypeptide described herein or a composition thereof and/or one or more of the nucleic acids, vectors, VLPs, or virosomes described herein, are administered to an infant, wherein the influenza virus hemagglutinin head domain of the chimeric influenza hemagglutinin (HA) polypeptide used in the first dose is from a different strain or subtype than the influenza virus hemagglutinin head domain of the chimeric influenza hemagglutinin (HA) polypeptide used in the second dose. The first and second administrations may be separated by at least 1 day, 2 days, 3 days, 5 days, 10 days, 15 days, 30 days, 45 days, 2 months, 75 days, 3 months, or at least 6 months.

**[00392]** In a specific embodiment, for administration to human infants, three doses of a chimeric influenza hemagglutinin (HA) polypeptide described herein described herein or a composition thereof and/or one or more of the nucleic acids, vectors, VLPs, or virosomes described herein, are administered to an infant, wherein the influenza virus hemagglutinin head

domains of the chimeric influenza hemagglutinin (HA) polypeptides used in the first, second, and third doses are from different strains or subtypes of influenza virus. The first, second, and third administrations may be separated by at least 1 day, 2 days, 3 days, 5 days, 10 days, 15 days, 30 days, 45 days, 2 months, 75 days, 3 months, or at least 6 months.

**[00393]** In particular embodiments, an active compound (e.g, a chimeric influenza hemagglutinin (HA) polypeptide described herein, a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, cells stimulated with such a polypeptide) or composition is administered to a subject in the fall or winter, *i.e.*, prior to or during the influenza season in each hemisphere. In one embodiment, children are administered their first dose early in the season, *e.g.*, late September or early October in the Northern hemisphere, so that the second dose can be given prior to the peak of the influenza season.

**[00394]** For passive immunization with an antibody (e.g., an antibody generated and/or identified using a chimeric influenza hemagglutinin (HA) polypeptide described herein), the dosage ranges from about 0.0001 to 100 mg/kg, and more usually 0.01 to 5 mg/kg, of the patient body weight. For example, dosages can be 1 mg/kg body weight or 10 mg/kg body weight or within the range of 1-10 mg/kg or in other words, 70 mg or 700 mg or within the range of 70-700 mg, respectively, for a 70 kg patient. An exemplary treatment regime entails administration once per every two weeks or once a month or once every 3 to 6 months for a period of one year or over several years, or over several year-intervals. In some methods, two or more monoclonal antibodies with different binding specificities are administered simultaneously, in which case the dosage of each antibody administered falls within the ranges indicated. Antibody is usually administered on multiple occasions. Intervals between single dosages can be weekly, monthly or yearly. Intervals can also be irregular as indicated by measuring blood levels of antibody to the chimeric influenza hemagglutinin (HA) polypeptide in the patient.

## 5.13 BIOLOGICAL ASSAYS

### 5.13.1 Assays For Testing Activity Of Chimeric Influenza Virus Hemagglutinin Polypeptides

**[00395]** Assays for testing the expression of a chimeric influenza hemagglutinin (HA) polypeptide in a vector disclosed herein may be conducted using any assay known in the art. For

example, an assay for incorporation into a viral vector comprises growing the virus, purifying the viral particles by centrifugation through a sucrose cushion, and subsequent analysis for chimeric influenza hemagglutinin (HA) polypeptide expression by an immunoassay, such as Western blotting, using methods well known in the art. Methods for determining whether a hemagglutinin polypeptide is chimeric are known to those of skill in the art and described herein.

**[00396]** In one embodiment, a chimeric influenza hemagglutinin (HA) polypeptide disclosed herein is assayed for proper folding and functionality by testing its ability to bind specifically to a neutralizing antibody directed to an influenza virus hemagglutinin polypeptide, such as the stalk region of the polypeptide, using any assay for antibody-antigen interaction known in the art. Neutralizing antibodies for use in such assays include, for example, the neutralizing antibodies described in Ekiert *et al.*, 2009, *Science Express*, 26 February 2009; Kashyap *et al.*, 2008, *Proc Natl Acad Sci U S A* 105: 5986-5991; Sui *et al.* 2009, *Nature Structural and Molecular Biology*, 16:265-273; Wang *et al.*, 2010, *PLOS Pathogens* 6(2):1-9; U.S. Patent Nos. 5,589,174, 5,631,350, 6,337,070, and 6,720,409; International Application No. PCT/US2007/068983 published as International Publication No. WO 2007/134237; International Application No. PCT/US2008/075998 published as International Publication No. WO 2009/036157; International Application No. PCT/EP2007/059356 published as International Publication No. WO 2008/028946; and International Application No. PCT/US2008/085876 published as International Publication No. WO 2009/079259.. These antibodies include CR6261, CR6325, CR6329, CR6307, CR6323, 2A, D7, D8, F10, G17, H40, A66, D80, E88, E90, H98, C179 (FERM BP-4517), AI3C (FERM BP-4516), CR8114, CR8020 (Ekiert *et al.,* 2011. *Science*. 333(6044): 843-850), FI6 (Corti *et al.,* 2011. *Science*. 333(6044) 850-856, DOI: 10.1126/science.1205669), the influenza B virus stalk mAbs 3A2, 10C4, or 5A7 (Yasugi *et al.,* 2013. *PLoS Pathog.* 9(2): e1003150) among others.

**[00397]** In another embodiment, a chimeric influenza hemagglutinin (HA) polypeptide disclosed herein is assayed for proper folding by determination of the structure or conformation of the chimeric influenza hemagglutinin (HA) polypeptide using any method known in the art such as, *e.g.*, NMR, X-ray crystallographic methods, or secondary structure prediction methods, *e.g.*, circular dichroism.

### 5.13.2 Assays For Testing Activity Of Antibodies Generated Using Chimeric Influenza Virus Hemagglutinin Polypeptides

**[00398]** Antibodies described herein may be characterized in a variety of ways known to one of skill in the art (e.g. ELISA, Surface Plasmon resonance display (BIAcore), Western blot, immunofluorescence, immunostaining and/or microneutralization assays). In some embodiments, antibodies are assayed for the ability to specifically bind to a chimeric influenza hemagglutinin (HA) polypeptide, or a vector comprising said polypeptide. Such an assay may be performed in solution (e.g., Houghten, 1992, Bio/Techniques 13:412 421), on beads (Lam, 1991, Nature 354:82 84), on chips (Fodor, 1993, Nature 364:555 556), on bacteria (U.S. Patent No. 5,223,409), on spores (U.S. Patent Nos. 5,571,698; 5,403,484; and 5,223,409), on plasmids (Cull *et al.*, 1992, Proc. Natl. Acad. Sci. USA 89:1865 1869) or on phage (Scott and Smith, 1990, Science 249:386 390; Cwirla *et al.*, 1990, Proc. Natl. Acad. Sci. USA 87:6378 6382; and Felici, 1991, J. Mol. Biol. 222:301 310) (each of these references is incorporated herein in its entirety by reference).

**[00399]** Specific binding of an antibody to the chimeric influenza hemagglutinin (HA) polypeptide and cross-reactivity with other antigens can be assessed by any method known in the art. Immunoassays which can be used to analyze specific binding and cross-reactivity include, but are not limited to, competitive and non-competitive assay systems using techniques such as western blots, radioimmunoassays, ELISA (enzyme linked immunosorbent assay), "sandwich" immunoassays, immunoprecipitation assays, precipitin reactions, gel diffusion precipitin reactions, immunodiffusion assays, agglutination assays, complement-fixation assays, immunoradiometric assays, fluorescent immunoassays, protein A immunoassays, to name but a few. Such assays are routine and well known in the art (see, e.g., Ausubel *et al.*, eds., 1994, Current Protocols in Molecular Biology, Vol. 1, John Wiley & Sons, Inc., New York, which is incorporated by reference herein in its entirety).

**[00400]** The binding affinity of an antibody to a chimeric influenza hemagglutinin (HA) polypeptide and the off-rate of an antibody-antigen interaction can be determined by competitive binding assays. One example of a competitive binding assay is a radioimmunoassay comprising the incubation of labeled antigen (e.g., $^{3}H$ or $^{125}I$) with the antibody of interest in the presence of increasing amounts of unlabeled antigen, and the detection of the antibody bound to the labeled antigen. The affinity of the antibody for a chimeric influenza hemagglutinin (HA) polypeptide and the binding off-rates can be determined from the data by Scatchard plot analysis. Competition with a second antibody can also be determined using radioimmunoassays. In this

case, a chimeric influenza hemagglutinin (HA) polypeptide is incubated with the test antibody conjugated to a labeled compound (e.g., $^{3}H$ or $^{125}I$) in the presence of increasing amounts of an unlabeled second antibody.

**[00401]** In certain embodiments, antibody binding affinity and rate constants are measured using the KinExA 3000 System (Sapidyne Instruments, Boise, ID). In some embodiments, surface plasmon resonance (*e.g.*, BIAcore kinetic) analysis is used to determine the binding on and off rates of the antibodies to an influenza virus hemagglutinin polypeptide. BIAcore kinetic analysis comprises analyzing the binding and dissociation of a chimeric influenza hemagglutinin (HA) polypeptide from chips with immobilized antibodies to chimeric influenza hemagglutinin (HA) polypeptide on their surface. A typical BIAcore kinetic study involves the injection of 250 μL of an antibody reagent (mAb, Fab) at varying concentration in HBS buffer containing 0.005% Tween-20 over a sensor chip surface, onto which has been immobilized the chimeric influenza hemagglutinin (HA) polypeptide. The flow rate is maintained constant at 75 μL/min. Dissociation data is collected for 15 min or longer as necessary. Following each injection/dissociation cycle, the bound antibody is removed from the influenza virus hemagglutinin polypeptide surface using brief, 1 min pulses of dilute acid, typically 10-100 mM HCl, though other regenerants are employed as the circumstances warrant. More specifically, for measurement of the rates of association, $k_{on}$, and dissociation, $k_{off}$, the polypeptide is directly immobilized onto the sensor chip surface through the use of standard amine coupling chemistries, namely the EDC/NHS method (EDC= N-diethylaminopropyl)-carbodiimide). Briefly, a 5-100 nM solution of the polypeptide in 10 mM NaOAc, pH 4 or pH 5 is prepared and passed over the EDC/NHS-activated surface until approximately 30-50 RU's worth of polypeptide are immobilized. Following this, the unreacted active esters are "capped" off with an injection of 1M Et-$NH_2$. A blank surface, containing no polypeptide, is prepared under identical immobilization conditions for reference purposes. Once an appropriate surface has been prepared, a suitable dilution series of each one of the antibody reagents is prepared in HBS/Tween-20, and passed over both the polypeptide and reference cell surfaces, which are connected in series. The range of antibody concentrations that are prepared varies, depending on what the equilibrium binding constant, $K_D$, is estimated to be. As described above, the bound antibody is removed after each injection/dissociation cycle using an appropriate regenerant.

**[00402]** The neutralizing activity of an antibody can be determined utilizing any assay known to one skilled in the art. Antibodies described herein can be assayed for their ability to inhibit the binding of an influenza virus, or any other composition comprising a chimeric influenza hemagglutinin (HA) polypeptide (*e.g.*, a VLP, liposome, or detergent extract), to its host cell receptor (*i.e.*, sialic acid) using techniques known to those of skill in the art. For example, cells expressing influenza virus receptors can be contacted with a composition comprising a chimeric influenza hemagglutinin (HA) polypeptide described herein in the presence or absence of the antibody and the ability of the antibody to inhibit the antigen's binding can measured by, for example, flow cytometry or a scintillation assay. The composition comprising a chimeric influenza hemagglutinin (HA) polypeptide described herein or the antibody can be labeled with a detectable compound such as a radioactive label (e.g., $^{32}P$, $^{35}S$, and $^{125}I$) or a fluorescent label (e.g., fluorescein isothiocyanate, rhodamine, phycoerythrin, phycocyanin, allophycocyanin, o-phthaldehyde and fluorescamine) to enable detection of an interaction between the composition comprising a chimeric influenza hemagglutinin (HA) polypeptide described herein and a cell receptor. Alternatively, the ability of antibodies to inhibit a chimeric influenza hemagglutinin (HA) polypeptide described herein from binding to its receptor can be determined in cell-free assays. For example, a composition comprising a chimeric influenza hemagglutinin (HA) polypeptide described herein can be contacted with an antibody and the ability of the antibody to inhibit the composition comprising the chimeric influenza hemagglutinin (HA) polypeptide from binding to a cell receptor can be determined. In a specific embodiment, the antibody is immobilized on a solid support and the composition comprising an influenza virus hemagglutinin polypeptide is labeled with a detectable compound. Alternatively, a composition comprising a chimeric influenza hemagglutinin (HA) polypeptide described herein is immobilized on a solid support and the antibody is labeled with a detectable compound. In certain embodiments, the ability of an antibody to inhibit a chimeric influenza hemagglutinin (HA) polypeptide described herein from binding to a cell receptor is determined by assessing the percentage of binding inhibition of the antibody relative to a control (e.g., an antibody known to inhibit the chimeric influenza hemagglutinin (HA) polypeptide from binding to the cell receptor).

**[00403]** In other embodiments, an antibody suitable for use in the methods described herein does not inhibit influenza virus receptor binding, yet is still found to be neutralizing in an assay described herein. In some embodiments, an antibody suitable for use in accordance with the

methods described herein reduces or inhibits virus-host membrane fusion in an assay known in the art or described herein.

**[00404]** In one embodiment, virus-host membrane fusion is assayed in an *in vitro* assay using an influenza virus containing a reporter and a host cell capable of being infected with the virus. An antibody inhibits fusion if reporter activity is inhibited or reduced compared to a negative control (*e.g.*, reporter activity in the presence of a control antibody or in the absence of antibody).

**[00405]** In one embodiment, virus-host membrane fusion is detected using a model system of cell fusion. In an exemplary cell fusion assay, cells (*e.g.*, HeLa cells) are transfected with a plasmid encoding a chimeric influenza hemagglutinin (HA) polypeptide described herein and contacted and exposed to a buffer that allows the chimeric influenza hemagglutinin (HA) polypeptide fusion function (*e.g.*, pH 5.0 buffer) in the presence of an antibody. An antibody is neutralizing if it reduces or inhibits syncytia formation compared to a negative control (*e.g.*, syncytia formation in the presence of a control antibody or in the absence of antibody).

**[00406]** In other embodiments, virus-host membrane fusion is assayed using an *in vitro* liposome-based assay. In an exemplary assay, the host cell receptor is reconstituted into liposomes containing one half of a reporter. A chimeric influenza hemagglutinin (HA) polypeptide described herein is reconstituted into another set of liposomes containing another half of a reporter. When the two liposome populations are mixed together, fusion is detected by reconstitution of the reporter, for example, an enzymatic reaction that can be detected colorimetrically. The antibody inhibits fusion if reporter activity is reduced or inhibited compared to reporter activity in an assay conducted in the absence of antibody or in the presence of a control antibody. In certain embodiments, the ability of an antibody to inhibit fusion is determined by assessing the percentage of fusion in the presence of the antibody relative to the percentage of fusion in the presence a control.

### 5.13.3 Assays for Testing Activity of Stimulated Cells

**[00407]** Cells stimulated in accordance with the methods described herein may be analyzed, for example, for integration, transcription and/or expression of the polynucleotide or gene(s) of interest, the number of copies of the gene integrated, and the location of the integration. Such analysis may be carried out at any time and may be carried out by any methods known in the art. In other embodiments, successful stimulation of the target cell with a chimeric influenza

hemagglutinin (HA) polypeptide described herein is determined by detecting production of neutralizing antibodies against the chimeric influenza hemagglutinin (HA) polypeptide using methods known in the art or described herein.

**[00408]** In certain embodiments, subjects in which the stimulated cells, e.g., DCs, are administered can be analyzed for location of the cells, expression of a vector-delivered polynucleotide or gene encoding the chimeric influenza hemagglutinin (HA) polypeptide, stimulation of an immune response (e.g., production of neutralizing antibodies against the chimeric influenza hemagglutinin (HA) polypeptide), and/or monitored for symptoms associated with influenza virus infection or a disease associated therewith by any methods known in the art or described herein.

**[00409]** Reporter assays can be used to determine the specificity of the targeting of the chimeric influenza hemagglutinin (HA) polypeptide described herein. For example, a mixed population of bone marrow cells can be obtained from a subject and cultured in vitro. The chimeric influenza hemagglutinin (HA) polypeptide can be administered to the mixed population of bone marrow cells, and expression of a reporter gene associated with the fl chimeric influenza hemagglutinin (HA) polypeptide can be assayed in the cultured cells. In some embodiments, at least about 50%, more preferably at least about 60%, 70%, 80% or 90%, still more preferably at least about 95% of stimulated cells in the mixed cell population are dendritic cells.

### 5.13.4 Antiviral Activity Assays

**[00410]** Antibodies described herein or compositions thereof can be assessed *in vitro* for antiviral activity. In one embodiment, the antibodies or compositions thereof are tested *in vitro* for their effect on growth of an influenza virus. Growth of influenza virus can be assessed by any method known in the art or described herein (e.g. in cell culture). In a specific embodiment, cells are infected at a MOI of 0.0005 and 0.001, 0.001 and 0.01, 0.01 and 0.1, 0.1 and 1, or 1 and 10, or a MOI of 0.0005, 0.001, 0.005, 0.01, 0.05, 0.1, 0.5, 1, 5 or 10 and incubated with serum free media supplemented. Viral titers are determined in the supernatant by hemagglutinin plaques or any other viral assay described herein. Cells in which viral titers can be assessed include, but are not limited to, EFK-2 cells, Vero cells, MDCK cells, primary human umbilical vein endothelial cells (HUVEC), H292 human epithelial cell line and HeLa cells. *In vitro* assays include those that measure altered viral replication (as determined, e.g., by plaque formation) or the production of viral proteins (as determined, e.g., by Western blot analysis) or viral RNAs (as

determined, e.g., by RT-PCR or northern blot analysis) in cultured cells in vitro using methods which are well known in the art or described herein.

**[00411]** In one non-limiting example, a monolayer of the target mammalian cell line is infected with different amounts (*e.g.*, multiplicity of 3 plaque forming units (pfu) or 5 pfu) of virus (*e.g.*, influenza) and subsequently cultured in the presence or absence of various dilutions of antibodies (*e.g.*, 0.1 μg/ml, 1 μg/ml, 5 μg/ml, or 10 μg/ml). Infected cultures are harvested 48 hours or 72 hours post infection and titered by standard plaque assays known in the art on the appropriate target cell line (*e.g.*, Vero cells).

**[00412]** In a non-limiting example of a hemagglutination assay, cells are contacted with an antibody and are concurrently or subsequently infected with the virus (*e.g.*, at an MOI of 1) and the virus is incubated under conditions to permit virus replication (*e.g.*, 20-24 hours). The antibodies are preferably present throughout the course of infection. Viral replication and release of viral particles is then determined by hemagglutination assays using 0.5% chicken red blood cells. See, *e.g.*, Kashyap *et al.*, PNAS USA 105: 5986-5991. In some embodiments, a compound is considered an inhibitor of viral replication if it reduces viral replication by at least 2 wells of HA, which equals approximately a 75% reduction in viral titer. In specific embodiments, an inhibitor reduces viral titer in this assay by 50% or more, by 55% or more, by 60% or more, by 65% or more, by 70% or more, by 75% or more, by 80% or more, by 85% or more, by 90% or more, or by 95% or more. In other specific embodiments an inhibitor results in a reduction of approximately 1 log or more, approximately 2 logs or more, approximately 3 logs or more, approximately 4 logs or more, approximately 5 logs or more, approximately 6 logs or more, approximately 7 logs or more, approximately 8 logs or more, approximately 9 logs or more, approximately 10 logs or more, 1 to 3 logs, 1 to 5 logs, 1 to 8 logs, 1 to 9 logs, 2 to 10 logs, 2 to 5 logs, 2 to 7 logs, 2 logs to 8 logs, 2 to 9 logs, 2 to 10 logs 3 to 5 logs, 3 to 7 logs, 3 to 8 logs, 3 to 9 logs, 4 to 6 logs, 4 to 8 logs, 4 to 9 logs, 5 to 6 logs, 5 to 7 logs, 5 to 8 logs, 5 to 9 logs, 6 to 7 logs, 6 to 8 logs, 6 to 9 logs, 7 to 8 logs, 7 to 9 logs, or 8 to 9 logs in influenza virus titer in the subject. The log-reduction in Influenza virus titer may be as compared to a negative control, as compared to another treatment, or as compared to the titer in the patient prior to antibody administration.

### 5.13.5 Cytotoxicity Assays

**[00413]** Many assays well-known in the art can be used to assess viability of cells (infected or uninfected) or cell lines following exposure to an active compound or a composition thereof and, thus, determine the cytotoxicity of the compound or composition. For example, cell proliferation can be assayed by measuring Bromodeoxyuridine (BrdU) incorporation (*See*, *e.g.*, Hoshino *et al.*, 1986, Int. J. Cancer 38, 369; Campana *et al.*, 1988, J. Immunol. Meth. 107:79), (3H) thymidine incorporation (*See*, *e.g.*, Chen, J., 1996, Oncogene 13:1395-403; Jeoung, J., 1995, J. Biol. Chem. 270:18367 73), by direct cell count, or by detecting changes in transcription, translation or activity of known genes such as proto-oncogenes (*e.g.*, fos, myc) or cell cycle markers (Rb, cdc2, cyclin A, D1, D2, D3, E, etc). The levels of such protein and mRNA and activity can be determined by any method well known in the art. For example, protein can be quantitated by known immunodiagnostic methods such as ELISA, Western blotting or immunoprecipitation using antibodies, including commercially available antibodies. mRNA can be quantitated using methods that are well known and routine in the art, for example, using northern analysis, RNase protection, or polymerase chain reaction in connection with reverse transcription. Cell viability can be assessed by using trypan-blue staining or other cell death or viability markers known in the art. In a specific embodiment, the level of cellular ATP is measured to determined cell viability.

**[00414]** In specific embodiments, cell viability is measured in three-day and seven-day periods using an assay standard in the art, such as the CellTiter-Glo Assay Kit (Promega) which measures levels of intracellular ATP. A reduction in cellular ATP is indicative of a cytotoxic effect. In another specific embodiment, cell viability can be measured in the neutral red uptake assay. In other embodiments, visual observation for morphological changes may include enlargement, granularity, cells with ragged edges, a filmy appearance, rounding, detachment from the surface of the well, or other changes. These changes are given a designation of T (100% toxic), PVH (partially toxic–very heavy–80%), PH (partially toxic–heavy–60%), P (partially toxic–40%), Ps (partially toxic–slight–20%), or 0 (no toxicity–0%), conforming to the degree of cytotoxicity seen. A 50% cell inhibitory (cytotoxic) concentration ($IC_{50}$) is determined by regression analysis of these data.

**[00415]** In a specific embodiment, the cells used in the cytotoxicity assay are animal cells, including primary cells and cell lines. In some embodiments, the cells are human cells. In certain embodiments, cytotoxicity is assessed in one or more of the following cell lines: U937, a

human monocyte cell line; primary peripheral blood mononuclear cells (PBMC); Huh7, a human hepatoblastoma cell line; 293T, a human embryonic kidney cell line; and THP-1, monocytic cells. In certain embodiments, cytotoxicity is assessed in one or more of the following cell lines: MDCK, MEF, Huh 7.5, Detroit, or human tracheobronchial epithelial (HTBE) cells.

**[00416]** Active compounds (e.g., chimeric influenza hemagglutinin (HA) polypeptides described herein) or compositions thereof can be tested for *in vivo* toxicity in animal models. For example, animal models, described herein and/or others known in the art, used to test the activities of active compounds can also be used to determine the *in vivo* toxicity of these compounds. For example, animals are administered a range of concentrations of active compounds. Subsequently, the animals are monitored over time for lethality, weight loss or failure to gain weight, and/or levels of serum markers that may be indicative of tissue damage (*e.g.*, creatine phosphokinase level as an indicator of general tissue damage, level of glutamic oxalic acid transaminase or pyruvic acid transaminase as indicators for possible liver damage). These *in vivo* assays may also be adapted to test the toxicity of various administration mode and/or regimen in addition to dosages.

**[00417]** The toxicity and/or efficacy of an active compound (e.g., chimeric influenza hemagglutinin (HA) polypeptides described herein) can be determined by standard pharmaceutical procedures in cell cultures or experimental animals, *e.g.*, for determining the $LD_{50}$ (the dose lethal to 50% of the population) and the $ED_{50}$ (the dose therapeutically effective in 50% of the population). The dose ratio between toxic and therapeutic effects is the therapeutic index and it can be expressed as the ratio $LD_{50}/ED_{50}$. An active compound that exhibits large therapeutic indices is preferred. While an active compound that exhibits toxic side effects may be used, care should be taken to design a delivery system that targets such agents to the site of affected tissue in order to minimize potential damage to uninfected cells and, thereby, reduce side effects.

**[00418]** The data obtained from the cell culture assays and animal studies can be used in formulating a range of dosage of an active compound for use in humans. The dosage of such agents lies preferably within a range of circulating concentrations that include the $ED_{50}$ with little or no toxicity. The dosage may vary within this range depending upon the dosage form employed and the route of administration utilized. For any active compound used in a method described herein, the effective dose can be estimated initially from cell culture assays. A dose

may be formulated in animal models to achieve a circulating plasma concentration range that includes the $IC_{50}$ (*i.e.*, the concentration of the test compound that achieves a half-maximal inhibition of symptoms) as determined in cell culture. Such information can be used to more accurately determine useful doses in humans. Levels in plasma may be measured, for example, by high-performance liquid chromatography. Additional information concerning dosage determination is provided herein.

**[00419]** Further, any assays known to those skilled in the art can be used to evaluate the prophylactic and/or therapeutic utility of the active compounds and compositions described herein, for example, by measuring viral infection or a condition or symptoms associated therewith.

### 5.13.6 In vivo Antiviral Activity

**[00420]** Active compounds (e.g., chimeric influenza hemagglutinin (HA) polypeptides described herein) and compositions thereof can be assayed *in vivo* for the desired therapeutic or prophylactic activity prior to use in humans. For example, *in vivo* assays can be used to determine whether it is preferable to administer an active compound or composition thereof and/or another therapy. For example, to assess the use of an active compound or composition thereof to prevent an influenza virus disease, the composition can be administered before the animal is infected with influenza virus. Alternatively, or in addition, an active compound or composition thereof can be administered to the animal at the same time that the animal is infected with influenza virus. To assess the use of an active compound or composition thereof to treat an influenza virus infection or disease associated therewith, the compound or composition may be administered after infecting the animal with influenza virus. In a specific embodiment, an active compound or composition thereof is administered to the animal more than one time.

**[00421]** Active compounds (e.g., chimeric influenza hemagglutinin (HA) polypeptides described herein) and compositions thereof can be tested for antiviral activity in animal model systems including, but are not limited to, rats, mice, chicken, cows, monkeys, pigs, ferrets, goats, sheep, dogs, rabbits, guinea pigs, etc. In a specific embodiment, active compounds and compositions thereof are tested in a mouse model system. Such model systems are widely used and well-known to the skilled artisan. In a specific embodiment, active compounds and compositions thereof are tested in a mouse model system. Non-limiting examples of animal models for influenza virus are provided in this section.

**[00422]** In general, animals are infected with influenza virus and concurrently or subsequently treated with an active compound or composition thereof, or placebo. Alternatively, animals are treated with an active compound or composition thereof or placebo and subsequently infected with influenza virus. Samples obtained from these animals (*e.g.*, serum, urine, sputum, semen, saliva, plasma, or tissue sample) can be tested for viral replication via well known methods in the art, *e.g.*, those that measure altered viral titers (as determined, *e.g.*, by plaque formation), the production of viral proteins (as determined, *e.g.*, by Western blot, ELISA, or flow cytometry analysis) or the production of viral nucleic acids (as determined, *e.g.*, by RT-PCR or northern blot analysis). For quantitation of virus in tissue samples, tissue samples are homogenized in phosphate-buffered saline (PBS), and dilutions of clarified homogenates are adsorbed for 1 hour at 37°C onto monolayers of cells (*e.g.*, Vero, CEF or MDCK cells). In other assays, histopathologic evaluations are performed after infection, preferably evaluations of the organ(s) the virus is known to target for infection. Virus immunohistochemistry can be performed using a viral-specific monoclonal antibody.

**[00423]** The effect of an active compound (e.g., chimeric influenza hemagglutinin (HA) polypeptides described herein) or composition thereof on the virulence of a virus can also be determined using *in vivo* assays in which the titer of the virus in an infected subject administered an active compound or composition thereof, the length of survival of an infected subject administered an active compound or composition thereof, the immune response in an infected subject administered an active compound or composition thereof, the number, duration and/or severity of the symptoms in an infected subject administered an active compound or composition thereof, and/or the time period before onset of one or more symptoms in an infected subject administered an active compound or composition thereof, is assessed. Techniques known to one of skill in the art can be used to measure such effects. In certain embodiments, an active compound or composition thereof results in a 0.5 fold, 1 fold, 2 fold, 4 fold, 6 fold, 8 fold, 10 fold, 15 fold, 20 fold, 25 fold, 50 fold, 75 fold, 100 fold, 125 fold, 150 fold, 175 fold, 200 fold, 300 fold, 400 fold, 500 fold, 750 fold, or 1,000 fold or greater reduction in titer of influenza virus relative to an untreated subject. In some embodiments, an active compound or composition thereof results in a reduction in titer of influenza virus relative to an untreated subject of approximately 1 log or more, approximately 2 logs or more, approximately 3 logs or more, approximately 4 logs or more, approximately 5 logs or more, approximately 6 logs or more,

approximately 7 logs or more, approximately 8 logs or more, approximately 9 logs or more, approximately 10 logs or more, 1 to 3 logs, 1 to 5 logs, 1 to 8 logs, 1 to 9 logs, 2 to 10 logs, 2 to 5 logs, 2 to 7 logs, 2 logs to 8 logs, 2 to 9 logs, 2 to 10 logs 3 to 5 logs, 3 to 7 logs, 3 to 8 logs, 3 to 9 logs, 4 to 6 logs, 4 to 8 logs, 4 to 9 logs, 5 to 6 logs, 5 to 7 logs, 5 to 8 logs, 5 to 9 logs, 6 to 7 logs, 6 to 8 logs, 6 to 9 logs, 7 to 8 logs, 7 to 9 logs, or 8 to 9 logs.

**[00424]** Influenza virus animal models, such as ferret, mouse, guinea pig, squirrel monkey, macaque, and chicken, developed for use to test antiviral agents against influenza virus have been described. *See, e.g.*, Sidwell *et al.*, Antiviral Res., 2000, 48:1-16; Lowen A.C. *et al.* PNAS., 2006, 103: 9988-92; and McCauley *et al.*, Antiviral Res., 1995, 27:179-186 and Rimmelzwann *et al.*, Avian Diseases, 2003, 47:931-933. For mouse models of influenza, non-limiting examples of parameters that can be used to assay antiviral activity of active compounds administered to the influenza-infected mice include pneumonia-associated death, serum α1-acid glycoprotein increase, animal weight, lung virus assayed by hemagglutinin, lung virus assayed by plaque assays, and histopathological change in the lung. Statistical analysis is carried out to calculate significance (*e.g.*, a P value of 0.05 or less).

**[00425]** In other assays, histopathologic evaluations are performed after infection of an animal model subject. Nasal turbinates and trachea may be examined for epithelial changes and subepithelial inflammation. The lungs may be examined for bronchiolar epithelial changes and peribronchiolar inflammation in large, medium, and small or terminal bronchioles. The alveoli are also evaluated for inflammatory changes. The medium bronchioles are graded on a scale of 0 to 3+ as follows: 0 (normal: lined by medium to tall columnar epithelial cells with ciliated apical borders and basal pseudostratified nuclei; minimal inflammation); 1+ (epithelial layer columnar and even in outline with only slightly increased proliferation; cilia still visible on many cells); 2+ (prominent changes in the epithelial layer ranging from attenuation to marked proliferation; cells disorganized and layer outline irregular at the luminal border); 3+ (epithelial layer markedly disrupted and disorganized with necrotic cells visible in the lumen; some bronchioles attenuated and others in marked reactive proliferation).

**[00426]** The trachea is graded on a scale of 0 to 2.5+ as follows: 0 (normal: Lined by medium to tall columnar epithelial cells with ciliated apical border, nuclei basal and pseudostratified. Cytoplasm evident between apical border and nucleus. Occasional small focus with squamous cells); 1+ (focal squamous metaplasia of the epithelial layer); 2+ (diffuse squamous metaplasia

of much of the epithelial layer, cilia may be evident focally); 2.5+ (diffuse squamous metaplasia with very few cilia evident).

**[00427]** Virus immunohistochemistry is performed using a viral-specific monoclonal antibody (*e.g.* NP-, N- or HN-specific monoclonal antibodies). Staining is graded 0 to 3+ as follows: 0 (no infected cells); 0.5+ (few infected cells); 1+ (few infected cells, as widely separated individual cells); 1.5+ (few infected cells, as widely separated singles and in small clusters); 2+ (moderate numbers of infected cells, usually affecting clusters of adjacent cells in portions of the epithelial layer lining bronchioles, or in small sublobular foci in alveoli); 3+ (numerous infected cells, affecting most of the epithelial layer in bronchioles, or widespread in large sublobular foci in alveoli).

**[00428]** In one example, the ability to induce lung lesions and cause infection in an animal model of virus infection is compared using wild-type virus and mock virus. Lung lesions can be assessed as a percentage of lung lobes that are healthy by visual inspection. Animals are euthanized 5 days p.i. by intravenous administration of pentobarbital, and their lungs are removed in toto. The percentage of the surface of each pulmonary lobe that is affected by macroscopic lesions is estimated visually. The percentages are averaged to obtain a mean value for the 7 pulmonary lobes of each animal. In other assays, nasal swabs can be tested to determine virus burden or titer. Nasal swabs can be taken during necropsy to determine viral burden post-infection.

**[00429]** In one embodiment, virus is quantified in tissue samples. For example, tissue samples are homogenized in phosphate-buffered saline (PBS), and dilutions of clarified homogenates adsorbed for 1 h at 37°C onto monolayers of cells (e.g., MDCK cells). Infected monolayers are then overlaid with a solution of minimal essential medium containing 0.1% bovine serum albumin (BSA), 0.01% DEAE-dextran, 0.1% $NaHCO_3$, and 1% agar. Plates are incubated 2 to 3 days until plaques could be visualized. Tissue culture infectious dose (TCID) assays to titrate virus from PR8-infected samples are carried out as follows. Confluent monolayers of cells (e.g., MDCK cells) in 96-well plates are incubated with log dilutions of clarified tissue homogenates in media. Two to three days after inoculation, 0.05-ml aliquots from each well are assessed for viral growth by hemagglutination assay (HA assay).

#### 5.13.6.1.1 Assays in Humans

**[00430]** In one embodiment, an active compound (e.g., chimeric influenza hemagglutinin (HA) polypeptides described herein) or composition thereof that modulates replication of an influenza virus are assessed in infected human subjects. In accordance with this embodiment, an active compound or composition thereof is administered to the human subject, and the effect of the active compound or composition on viral replication is determined by, *e.g.*, analyzing the level of the virus or viral nucleic acids in a biological sample (*e.g.*, serum or plasma). An active compound or composition thereof that alters virus replication can be identified by comparing the level of virus replication in a subject or group of subjects treated with a control to that in a subject or group of subjects treated with an active compound or composition thereof. Alternatively, alterations in viral replication can be identified by comparing the level of the virus replication in a subject or group of subjects before and after the administration of an active compound or composition thereof. Techniques known to those of skill in the art can be used to obtain the biological sample and analyze the mRNA or protein expression.

**[00431]** In another embodiment, the effect of an active compound (e.g., chimeric influenza hemagglutinin (HA) polypeptides described herein) or composition thereof on the severity of one or more symptoms associated with an influenza virus infection/disease are assessed in an infected subject. In accordance with this embodiment, an active compound or composition thereof or a control is administered to a human subject suffering from influenza virus infection and the effect of the active compound or composition on one or more symptoms of the virus infection is determined. An active compound or composition thereof that reduces one or more symptoms can be identified by comparing the subjects treated with a control to the subjects treated with the active compound or composition. In a specific embodiment, administration of an active compound (e.g., chimeric influenza hemagglutinin (HA) polypeptides described herein) or composition thereof results in a decrease in hospitalization of a human or population of humans caused by influenza virus disease or infection. In another specific embodiment, administration of an active compound or composition thereof results in a reduced need for respiratory/breathing assistance in a human or population of humans with an influenza virus disease or infection. In another specific embodiment, administration of an active compound or composition thereof results in a reduced length of illness of a human or population of humans with an influenza virus disease or infection. In another specific embodiment, administration of an active compound or composition thereof results in improvement (e.g., an increase) in lung

volume as assessed by, e.g., whole body or lung plethysmography. In another embodiment, an active compound or composition thereof is administered to a healthy human subject and monitored for efficacy as a vaccine (e.g., the subject is monitored for the onset of symptoms of influenza virus infection; the ability of influenza virus to infect the subject; and/or a reduction in/absence of one or more symptoms associated with influenza virus infection). Techniques known to physicians familiar with infectious diseases can be used to determine whether an ative compound or composition thereof reduces one or more symptoms associated with the influenza virus disease.

## 5.14 ASSESSMENT OF ANTIBODIES IN A SUBJECT

**[00432]** In another aspect, a chimeric influenza hemagglutinin (HA) polypeptide described herein, or virus expressing a chimeric influenza hemagglutinin (HA) polypeptide described herein, can be used to assess the antibody response of a subject (e.g., a naive subject or an immunized/vaccinated subject) or a population of subjects to an influenza virus hemagglutinin polypeptide (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described herein). In specific embodiments, a chimeric influenza virus hemagglutinin polypeptide or a virus expressing a chimeric influenza virus hemagglutinin polypeptide can be used to assess the presence of stem-specific antibodies in the subject or population of subjects.

**[00433]** In a specific embodiment, the antibody response of a subject or a population of subjects that has been an immunized/vaccinated with an influenza virus hemagglutinin polypeptide (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described herein, or a virus expressing a chimeric influenza hemagglutinin (HA) polypeptide described herein), is assessed to identify the types of stalk-specific antibodies in the subject or population of subjects. Such an assessment may allow for the identification surrogate markers/endpoints important in determining the clinical response to administration of an influenza virus HA polypeptide polypeptide(s) (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described herein, or a virus expressing a chimeric influenza hemagglutinin (HA) polypeptide described herein) described herein. In such an approach, a biological sample, e.g., blood, from the subject or population of subjects may be isolated and tested directly for the presence of antibodies, or may be processed (e.g., to obtain sera) and subsequently tested for the presence of antibodies. Such antibody testing can utilize assays known in the art, e.g., ELISA.

**[00434]** In another specific embodiment, the antibody profile of a naive subject (i.e., a subject that has not been immunized/vaccinated with an influenza virus HA polypeptide polypeptide(s) (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described herein), or a virus expressing an influenza virus HA polypeptide polypeptide(s) (e.g., a chimeric influenza hemagglutinin (HA) polypeptide described herein)) or a population of naive subjects is assessed to determine whether said subject or population of subjects possesses globular head-specific and/or stem specific antibodies against various influenza virus strains or subtypes. Such an assessment may allow for the generation of a chimeric influenza hemagglutinin (HA) polypeptide, or viruses expressing chimeric influenza hemagglutinin (HA) polypeptides, that are suitable for administration to said subject or population of subjects. Such an assessment may determine an immunization strategy for the patient.

**[00435]** In another specific embodiment, provided herein is a method of assessing/detecting the presence of antibodies in a subject that are specific for a stem domain of a particular influenza virus strain or subtype comprising contacting *in vitro* a biological sample (e.g., blood, sera) from said subject with a chimeric influenza virus hemagglutinin polypeptide described herein, wherein said chimeric influenza virus hemagglutinin polypeptide comprises a stem domain from the strain or subtype of interest. In another specific embodiment, provided herein is a method of assessing/detecting the presence of antibodies in a subject that are specific for a stem domain of a particular influenza virus strain or subtype comprising contacting *in vitro* a biological sample (e.g., blood, sera) from said subject with a virus expressing/containing a chimeric influenza virus hemagglutinin polypeptide described herein, wherein said chimeric influenza virus hemagglutinin polypeptide comprises a stem domain from the strain or subtype of interest.

## 5.15 KITS

**[00436]** Provided herein is a pharmaceutical pack or kit comprising one or more containers filled with one or more of the ingredients of the pharmaceutical/immunogenic compositions described herein, such as one or more active compounds provided herein. Optionally associated with such container(s) can be a notice in the form prescribed by a governmental agency regulating the manufacture, use or sale of pharmaceuticals or biological products, which notice reflects approval by the agency of manufacture, use or sale for human administration.

**[00437]** The kits encompassed herein can be used in accordance with the methods described herein. In one embodiment, a kit comprises an active compound described herein, preferably one or more chimeric influenza hemagglutinin (HA) polypeptide described herein, in one or more containers. In certain embodiments, a kit comprises a vaccine described herein, e.g., a split virus vaccine, a subunit vaccine, an inactivated influenza virus vaccine, or a live influenza virus vaccine, wherein said vaccine comprises one or more chimeric influenza hemagglutinin (HA) polypeptides described herein. In a specific embodiment, provided herein are kits comprising a chimeric influenza virus hemagglutinin polypeptide described herein and instructions for using the chimeric influenza virus hemagglutinin polypeptide to assess the antibodies present in a subject. In another specific embodiment, provided herein are kits comprising a chimeric influenza virus hemagglutinin polypeptide described herein for use in methods of assaying for the presence of HA stem domain specific antibodies in a sample.

**[00438]** In a specific embodiment, a kit provided herein comprises a cH5/1 chimeric influenza hemagglutinin polypeptide described herein (or a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, or cells stimulated with such a polypeptide), a cH5/3 chimeric influenza hemagglutinin polypeptide described herein (or a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, or cells stimulated with such a polypeptide), a cH7/3 chimeric influenza hemagglutinin polypeptide described herein (or a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, or cells stimulated with such a polypeptide), a cH5/B chimeric influenza hemagglutinin polypeptide described herein (or a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, or cells stimulated with such a polypeptide), a cH7/B chimeric influenza hemagglutinin polypeptide described herein (or a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector or a bacteria) containing or expressing such a polypeptide, or cells stimulated with such a polypeptide), a cHB/B chimeric influenza hemagglutinin polypeptide described herein (or a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, or cells stimulated with such a polypeptide), or a cH4/3 chimeric influenza hemagglutinin polypeptide described herein (or a

nucleic acid encoding such a polypeptide, a vector (e.g., a viral vector or a bacteria) containing or expressing such a polypeptide or cells stimulated with such a polypeptide..

**[00439]** In another specific embodiment, a kit provided herein comprises a combination of a cH5/1 chimeric influenza hemagglutinin polypeptide described herein (or a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, or cells stimulated with such a polypeptide) and a cH5/3 chimeric influenza hemagglutinin polypeptide described herein (or a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, or cells stimulated with such a polypeptide); or a combination of a cH5/1 chimeric influenza hemagglutinin polypeptide described herein (or a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, or cells stimulated with such a polypeptide) and a cH7/3 chimeric influenza hemagglutinin polypeptide described herein (or a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, or cells stimulated with such a polypeptide).

**[00440]** In another specific embodiment, a kit provided herein comprises a combination of a cH5/1 chimeric influenza hemagglutinin polypeptide described herein (or a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, or cells stimulated with such a polypeptide) and a cH5/3 chimeric influenza hemagglutinin polypeptide described herein (or a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, or cells stimulated with such a polypeptide) and either of a cH5/B, a cH7/B, or a cB/B chimeric influenza hemagglutinin polypeptide described herein (or a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, or cells stimulated with such a polypeptide).

**[00441]** In another specific embodiment, a kit provided herein comprises a combination of a cH5/1 chimeric influenza hemagglutinin polypeptide described herein (or a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, or cells stimulated with such a polypeptide) and a cH7/3 chimeric influenza hemagglutinin polypeptide described herein (or a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, or cells

stimulated with such a polypeptide) and either of a cH5/B, a cH7/B, or a cB/B chimeric influenza hemagglutinin polypeptide described herein (or a nucleic acid encoding such a polypeptide, a vector (*e.g.*, a viral vector, or a bacteria) containing or expressing such a polypeptide, or cells stimulated with such a polypeptide).

## 6. EXAMPLES

### 6.1 EXAMPLE 1: CHIMERIC INFLUENZA VIRUS HEMAGGLUTININ POLYPEPTIDES

**[00442]** This example describes chimeric influenza virus hemagglutinin polypeptides and methods for inducing high levels of cross-neutralizing HA stalk antibodies in a subject comprising administration of said chimeric influenza virus hemagglutinin polypeptides. As described in this example, chimeric influenza virus hemagglutinin were generated that were successfully expressed by influenza virus and by cells engineered to express the chimeric influenza virus hemagglutinin. The chimeric influenza virus hemagglutinin were successfully recovered in their proper conformation, as evidenced by antibody recognition of both the stem and head domains of the chimeric influenza virus hemagglutinin.

**[00443]** Figure 2 depicts chimeric influenza virus hemagglutinins (HAs), comprising the stem/stalk domain of an H1 subtype of influenza virus and the heterologous globular head domains of other influenza virus subtypes (H2, H3, and H5). Following the strategy outline in Figure 2, an influenza virus was generated that comprises a chimeric HA composed of a stem domain derived from an H1N1 (PR8-H1N1) influenza virus and the globular head domain of the 2009 pandemic H1 HA (Cal/09). The globular head domains of the HAs of the two viruses are very distinct (~70% amino acid identity) whereas the stem domains are highly conserved but still divergent (~89% amino acid identity). As demonstrated in Figure 3, the chimeric HAs with the same stem domain but very different HA heads within the same subtype were expressed.

**[00444]** In addition, a chimeric HA consisting of the stalk domain of A/PR/8/34 HA and the globular head domain of HK/68 (chimeric H3) as well as wild type HAs (PR8-HA and HK68 HA) were expressed in 293T cells. Fig. 5 demonstrates that it is also possible to express stable chimeric HAs with the same stem domain (derived from the H1 subtype HA) and with a globular head from a different subtype (H3).

**[00445]** Thus, HA immunogens that completely share the HA stem domain but are highly divergent in their globular heads were designed. Repeated immunizations with these constructs should result in high levels of cross-neutralizing antibodies against the common stem domain of the HA. An improved vaccine strategy thus uses chimeric HAs with a constant stem/stalk domain and a changing globular head to induce robust cross-neutralizing anti-stem domain antibodies. A constant stem domain of, e.g., the H1 HA from A/PR/8/34 can be used together with globular heads from different group 1 HAs (H1, H2, H5, H9) to make a panel of either recombinant inactivated viruses, recombinant attenuated viruses or recombinant HAs (Figure 4). A similar panel for group 2 HAs based on the stem domain of, e.g., H3 HA of an X31 virus, in combination with H3, H4 and H7 globular heads can provide the basis for a group 2 HA universal vaccine. Recombinant viruses can be rescued on an influenza virus vaccine backbone, such as PR/8 or cold-adapted influenza viruses, grown by standard techniques and used as inactivated or attenuated vaccines. Recombinant HAs can be expressed in insect cells that are able to perform mammalian-like glycosylation (MIMIC Sf9) or by transient transfection of, e.g., 293 T or Vero cells, and then can be purified by Ni-chelat chromatography with the help of a C-terminal his tag. Other strategies can include the use of DNA vaccines expressing the chimeric HAs or other vectors, such as adenovirus vectors, expressing the chimeric HAs.

## 6.2 EXAMPLE 2: VIRUSES EXPRESSING CHIMERIC INFLUENZA VIRUS HEMAGGLUTININ POLYPEPTIDES

**[00446]** This example describes several functional chimeric influenza virus hemagglutinins encompassing a variety of globular head and stalk combinations from different hemagglutinin subtypes as well as recombinant influenza viruses expressing these chimeric hemagglutinins, which had growth properties similar to those of wild-type influenza viruses.

### 6.2.1 Materials and Methods

#### 6.2.1.1 Cells and viruses

**[00447]** 293T and MDCK cells were obtained from the American Type Culture Collection (ATCC, Manassas, VA) and were maintained either in Dulbecco's minimal essential medium (DMEM) or in MEM (Gibco, Invitrogen) supplemented with 10% fetal calf serum (HyClone; Thermo Scientific) and penicillin-streptomycin (Gibco, Invitrogen).

**[00448]** All A/PR/8/34 recombinant viruses were grown in 10-day old embryonated chicken eggs at 37°C for 2 days.

**6.2.1.2 Construction of plasmids**

**[00449]** Plasmids encoding the different chimeric hemagglutinins were constructed by a similar strategy adapted from constructing reverse genetics plasmids for generating recombinant viruses as previously described (see, e.g., Fodor et al., 1999, J Virol 73:9679-9682; and Hai et al., 2008, J Virol 82:10580-10590). Briefly, the different segments of chimeric HA were amplified by PCR with primers containing SapI sites, digested with SapI, and cloned into the SapI sites of the pDZ vector that contains the human RNA polymerase I promoter and the mouse RNA polymerase I terminator (see, e.g. Quinlivan et al., 2005, J Virol 79:8431-8439), through multi-segmental ligation.

**6.2.1.3 Flow cytometric analysis**

**[00450]** To assess levels of hemagglutinin proteins at the cell surface, 293T cells were transfected with 1 μg of the appropriate plasmid using Lipofectamine 2000 (Invitrogen) according to the manufacturer's instructions. At 24 h post-transfection, cells were trypsinized and resuspended in PBS containing 2% FBS prior to staining them with the monoclonal antibody (mAb) 6F12 against H1 HAs at a 1/1000 dilution or with the mAb 12D1 against H3 HAs (see Wang et al., 2010, PLoS Pathog 6:e1000796) at a 1/400 dilution. Stained cells were enumerated on a Beckman Coulter Cytomics FC 500 flow cytometer, and the results were analyzed using FlowJo software.

**6.2.1.4 Pseudoparticle generation and entry assay**

**[00451]** The procedure for pseudo-particle production was adapted from previous studies (see, e.g., Evans et al., 2007, Nature 446:801-805; and Sui et al., 2011, Clin Infect Dis 52:1003-1009). Briefly, 293-T cells were co-transfected with four plasmids encoding (i) a pro-virus containing the desired reporter (V1-GLuc), (ii) HIV Gag-Pol, (iii) the different chimeric hemagglutinin protein and (iv) influenza A PR8 neuraminidase (NA). Supernatants were collected 72 h post-transfection and subsequently, filtered (0.45 μm pore size). All transductions and infection assays using pseudo-particles were performed in the presence of 1 μg/ml polybrene (Sigma, St. Louis, MO) (see Sui et al., 2011, Clin Infect Dis 52:1003-1009).

**[00452]** The entry assay was performed through infecting MDCK cells with pseudo-particles with different chimeric hemagglutinin containing the G-Luc reporter. Twenty-four hours post-infection, cells were washed three times with fresh medium to remove G-Luc protein that was present in the pseudo-particle inoculum. Forty-eight hours post-infection luciferase assays were performed (see Evans et al., 2007, Nature 446:801-805).

**6.2.1.5 Rescue of recombinant chimeric Influenza A viruses**

**[00453]** Rescue of influenza A viruses from plasmid DNA was performed as previously described (see, e.g., Fodor et al., 1999, J Virol 73:9679-9682; and Hai et al., 2008, J Virol 82:10580-10590). To generate the recombinant wild-type (rWT) PR8 virus, 293T cells were co-transfected with 1 μg of each of the 8 pDZ PR8 rescue plasmids using Lipofectamine 2000 (Invitrogen, Carlsbad, CA). The viruses expressing different chimeric HA were generated in the same way but substituting the HA plasmid by the corresponding chimeric one to recover the corresponding chimeric viruses. At 6 h post-transfection, the medium was replaced with DMEM containing 0.3% bovine serum albumin (BSA), 10 mM HEPES, and 1.5 μg/ml TPCK (L-1-tosylamide-2-phenylethyl chloromethyl ketone)-treated trypsin. After 24 hours post-transfection, virus-containing supernatant was inoculated into 8-day old embryonated chicken eggs. Allantoic fluid was harvested after 2 days of incubation at 37°C and assayed for the presence of virus by hemagglutination of chicken red blood cells and by plaque formation in MDCK cells.

**6.2.1.6 Virus growth kinetics assay**

**[00454]** To analyze the replication characteristics of recombinant viruses, 10-day old embryonated chicken eggs were inoculated with 100 pfu of each respective virus. Allantoic fluid was harvested and subsequently assayed for viral growth at 0, 9, 24, 48, and 72 h post-infection (hpi). The titers of virus present in allantoic fluid were determined by plaque assay on MDCK cells.

**6.2.1.7 Immunostaining of plaques**

**[00455]** Plaques were visualized by immunostaining with the mAb (HT103) against the influenza A NP protein.

**6.2.1.8 Western blot and indirect immunofluorescence analysis**

**[00456]** One well of a 12-well dish of confluent MDCK cells was infected (multiplicity of infection [MOI] of 2) with indicated recombinant influenza viruses or mock infected with

phosphate-buffered saline (PBS) for 1 h at 37°C. At 12 h post-infection (hpi), cells were lysed in 1X protein loading buffer as described previously (see, e.g., Hai et al., 2008, J Virol 82:10580-10590). The reduced cell lysates were analyzed by Western blot analysis by using mAbs against, A/NP (HT103), A/PR8/HA (PY102), A/Cal/09/HA (29C1), A/VN/HA (M08) (20), A/H3/HA (12D1). The detection of Perth-cH7 used a goat polyclonal sera, NR-3152, against A/FPV/Dutch/27 (H7) virus, which was obtained from the BEI Resources. The mAb anti-Glyceraldehyde 3-phosphate dehydrogenase (GAPDH) loading control antibody was from Abcam. All the proteins of interest were visualized using an enhanced chemiluminescence protein detection system (PerkinElmer Life Sciences, Boston, MA).

**[00457]** For immunofluorescence analysis, confluent monolayers of MDCK cells on 15-mm coverslips were infected with recombinant viruses at an MOI of 2. At 15 hpi, cells were fixed and permeabilized with methanol-acetone (ratio, 1:1) at -20°C for 20 min. After being blocked with 1% bovine serum albumin in PBS containing 0.1% Tween 20, cells were incubated for 1 h with the antibody directed against A/NP (HT103), A/H1/HA (6F12), A/PR8/HA (PY102), A/Cal/09/HA (29C1), A/VN/HA (M08) (20), A/H3/HA (12D1), and A/H7 virus (NR-3152) as mentioned above. After three washes with PBS containing 0.1% Tween 20, cells were incubated for 1 h with Alexa Fluor 594-conjugated anti-mouse immunoglobulin G (IgG; Invitrogen, Carlsbad, CA) or Alexa Fluor 594-conjugated anti-goat immunoglobulin G (IgG, Invitrogen, Carlsbad, CA). Following the final three washes, infected cells were analyzed by fluorescence microscopy with an Olympus IX70 microscope.

### 6.2.2 Results

#### 6.2.2.1 Generation of chimeric hemagglutinins

**[00458]** In order to gain information regarding the conservation of the cysteine residues forming the Cys52-Cys277 disulfide bond, an alignment of the influenza A virus HA sequences of the H1, H3, H5 and H7 subtypes was generated (see Fig. 6). The sequences of the HA1 subunits are less conserved than those of the HA2 subunits, mainly due to the presence of immuno-dominant antigenic sites on the globular head domain. The more conserved HA2 chains comprise the stalk regions anchoring the HA molecules to the viral envelope. The alignment demonstrates that Cys52 and Cys277 and the amino acids towards both ends are conserved across selected subtypes. Henceforth, the hemagglutinin sequences N-terminal to Cys52 and C-

terminal to Cys277 are defined as the stalk domain (Fig 6). The intervening sequence is considered in this example to be the head domain.

**[00459]** A chimeric hemagglutinin construct (PR8-cH1) containing the pandemic H1 Cal/09 HA globular head domain with the stalk region from the PR8 (H1) HA was first generated (Fig. 7A). A chimeric HA (PR8-cH5) containing the globular head from the VN1203 (H5) HA with the stalk from the PR8 (H1) HA also was generated (Fig. 7B). Since all 16 subtypes of influenza HA are grouped into two phylogenetic groups (groups 1 and 2) (see, e.g., Sui et al., 2009, Nat Struct Mol Biol 16:265-273) and H1 and H5 HAs both belong to group 1, a similar strategy to generate a chimeric HA bearing the A/Alberta/24/01 (H7) head domain with the stalk region from A/Perth/16/2009 (H3) HA (Perth-cH7) (Fig. 7B) was applied. Both H7 and H3 are members from the group 2 phylogenetic group (see, e.g., Sui et al., 2009, Nat Struct Mol Biol 16:265-273).

**[00460]** It was next tested whether the different chimeric HA constructs were being expressed and transported to the cell surface. Fluorescence-activated cell sorter (FACS) analysis of transiently transfected 293T cells was performed following surface staining with PR8 and H3 stalk domain specific antibodies, respectively (Fig. 8A). As shown in Figure 8A, expression of all three chimeric constructs was detected. This detection indicates that the transportation of the chimeric HAs through the Golgi complex to the cell surface is not disrupted.

**[00461]** Next the entry characteristics of the different chimeric HAs was examined through infection of MDCK cells with retroviral HA-pseudotyped particles containing the chimeric HA, wild type influenza A PR8 NA and HIV-based luciferase. The entry efficiency mediated by the chimeric HA proteins was detected by luciferase read-out. Comparable levels of pseudotyped particle-mediated luciferase delivery were observed for PR8-cH5 and Perth-cH7 chimeric HAs and the corresponding wild type proteins (Fig 8B). The PR8-cH1 HA showed a lower luciferase level compared to the other HA constructs.

### 6.2.3 Generation of recombinant influenza viruses bearing chimeric hemagglutinins.

**[00462]** In light of the above results, whether a chimeric HA is functional in the context of a whole virus particle and ultimately would allow the rescue of a recombinant influenza A virus only expressing a chimeric HA was ascertained. Using previously published protocols (see, e.g., Fodor et al., 1999, J Virol 73:9679-9682; and Hai et al., 2008, J Virol 82:10580-10590), viruses containing all of the different chimeric HAs were successfully generated. The resulting viruses

were plaque purified, amplified in 10-Day-old embryonic eggs and the chimeric segments were analyzed by RT-PCR and sequenced. In all cases, the virus was found to have the expected chimeric HA segment and no other HA segments.

**[00463]** The identity of the chimeric viruses was further demonstrated by Western blotting and indirect immunofluorescence of infected cells (Fig. 9A and 9B). MDCK cells were infected with rWT A/PR8, wild-type A/Perth, PR8-cH1, PR8-cH5, and Perth-cH7 viruses (Fig. 9A and 9B). PR8-cH1 and PR8-cH5 chimeric HA proteins were detected in the corresponding samples using antibodies against either Cal/09 HA (29C1) or VN/04 HA (M08) (see Steel et al., 2009, J Virol 83:1742-1753), respectively (Fig. 9A). Using 12D1, a pan H3 stalk mAb (see Wang et al., 2010, PLoS Pathog 6:e1000796), comparable expression levels between the Perth cH7-HA and wild type Perth HA were observed. A positive band was only detected for the Perth-cH7 infection sample when using anti-H7 antibodies (NR-3152).

**[00464]** For the immunofluorescence study, the infection conditions were similar to those for the Western analysis. Infected cells were stained with corresponding antibodies as indicated in Figure 9B. All the infected cells showed the expected expression of the HAs as well as of the A/NP protein (Fig. 9B).

### 6.2.4 Replication characteristics of recombinant viruses

**[00465]** The growth properties of the viruses were assessed in 10-day-old embryonated chicken eggs at 37 °C (Fig 8A). The rWT PR8 virus was included for comparison of the growth kinetics of the recombinant viruses expressing chimeric HAs. Regarding the PR8-cH5 virus, a similar replication pattern as compared to PR8 virus was observed. As for Perth-cH7 virus, there was a 2 fold reduction in viral titer compared to the rWT PR8 virus at 9 hpi. Nevertheless, it reached a similar peak titer as the wild type virus ($1X10^9$ PFU/ml) at 48 hpi. The PR8-cH1 virus was attenuated when compared to the rWT PR8 virus, as shown by reduction in titers through all the time points. Nonetheless, even this chimeric virus reached a respectable peak titer of approximately $10^8$ PFU/ml. The plaque phenotype of each of the chimeric viruses was also evaluated in MDCK cells. All viruses formed comparably sized plaques as shown in Figure 8B. These results confirm that the chimeric HA constructs fold correctly in vivo and are biologically functional.

### 6.2.5 Conclusion

**[00466]** A novel strategy was developed to generate influenza viruses with chimeric HA proteins bearing different HA globular head domains by taking advantage of the conserved disulfide bond Cys52-Cys277 which demarcates the border between the head and stalk domains. Thus, through substituting the parental head domain with the head domain of another HA, a panel of chimeric HAs with the same stalk but different globular heads was generated. The design was tested across multiple subtypes, including the PR8 stalk domain with Cal/09 and VN H5 globular heads. In addition, an H7 globular head was placed on an H3 stalk domain. These constructs cover both phylogenetic groups of the influenza HA protein. Each construct was expressed on the cell surface and retained fusion activity as shown in Figure 7. The generation of recombinant viruses bearing the chimeric HAs further validated that the HAs fold correctly and retain biological functions.

## 6.3 EXAMPLE 3: DIAGNOSTIC APPLICATIONS OF CHIMERIC INFLUENZA VIRUS HEMAGGLUTININ POLYPEPTIDES AND VACCINATION OF MICE WITH CHIMERIC INFLUENZA VIRUS HEMAGGLUTININ POLYPEPTIDES

**[00467]** This example demonstrates that chimeric influenza virus hemagglutinin polypeptides can be utilized for diagnostic purposes and that viruses expressing chimeric influenza virus hemagglutinin polypeptides can be utilized in vaccines.

### 6.3.1 Materials and Methods

#### 6.3.1.1 Cells and plasmids

**[00468]** 293T and MDCK cells were obtained from ATCC and were maintained in Dulbeccos's Modified Eagle's medium (DMEM) and Minimal Essential Medium (both from Gibco), respectively, each supplemented with 10% fetal calf serum (HyClone), and 100 units/ml of penicillin-100 μg/ml of streptomycin (Pen/Strep, Gibco). TNM-FH (Sigma-Aldrich) supplemented with 10% fetal calf serum and Hyclone SFX insect culture media (ThermoScientific) were used for Sf9 and BTI-TN5B1-4 (High Five) cell culture.

**[00469]** Chimeric hemagglutinin constructs with the stalk of A/Puerto Rico/8/1934 (PR8) containing the globular head domain from either A/Mallard/Sweden/81/02 ("cH6") virus or A/Guinea fowl/Hong Kong/WF10/99 ("cH9") virus were generated using similar techniques. For the chimeric H6 construct, different components were amplified by PCR and cloned into the

pDZ plasmid using a cloning strategy previously described (see, e.g., Fodor et al., 1999, J Virol 73:9679-82; and Hai et al., 2008, Journal of Virology 82:10580-90). Briefly, different components of the chimeric hemagglutinin (cHA) were amplified by PCR with primers containing Sap I sites, digested with Sap I, and cloned into the Sap I sites of thepDZ plasmid. For generation of the baculo-transfer plasmid, cH6 was amplified by PCR, cut with BamHI and NotI, and cloned in frame into a modified pBacPAK8 (Gentech) baculo-transfer vector that harbors a C-terminal T4 phage foldon and a 6-his tag (see Meier et al., 2004, J Mol Biol 344:1051-69). The sequences of all plasmids were confirmed by Sanger sequencing.

**6.3.1.2 Rescue of recombinant cH9 virus**

**[00470]** In order to rescue the recombinant vaccine virus, eight reverse genetics plasmids that encode vRNA and mRNA of the seven wild type viral segments from PR8 and the cH9 were used, as previously described (Fodor et al., 1999, J Virol 73:9679-82; and Pleschka et al., 1996, J Virol 70:4188-92). Briefly, 293T cells were transfected with 1 μg of each of the eight plasmids using Lipofectamine 2000 (Invitrogen). At 12 hours post transfection, the medium was replaced with DMEM containing 0.3% bovine serum albumin, 10 mM HEPES, and 1.5 μg of TPCK (l-1-tosylamide-2-phenylethyl chloromethyl ketone)-treated trypsin/mL. At two days post transfection, virus-containing supernatant was inoculated into 10-day-old embryonated chicken eggs. Allantoic fluid was harvested after 2 days of incubation at 37° C and assayed for the presence of virus by the hemagglutination of chicken red blood cells. The rescued cH9 virus was then propagated in 10-day old eggs following a 48 hour incubation at 37°C. Virus stocks were tittered by plaque assay as previously described (see, e.g., Steel et al., 2009, Journal of Virology 83:1742-53). The sequence of the cH9 was confirmed by sequencing of reverse transcription-PCR products.

**6.3.1.3 Recombinant baculovirus generation, protein expression and purification**

**[00471]** In order to generate recombinant baculoviruses (rBV) carrying the cH6, plasmids and Baculogold DNA (BDBioschiences) were co-transfected into Sf9 cells with Cellfectin II (Invitrogen) according to the manufacturer's instructions. Recombinant baculovirus was amplified in Sf9 cells grown in TNM-FH medium (Gemini Bioproducts, West Sacramento, CA) and titers were determined by plaque assay as previously described (see, e.g., Steel et al., 2009, Journal of Virology 83:1742-53).

**[00472]** High Five cells (see Krammer et al., 2010, Mol Biotechnol 45:226-34) grown in HyClone SFX insect cell media (Thermo Fisher Scientific, Waltham, MA) were infected with rBV expressing cH6 at a multiplicity of infection (MOI) of 10 and a cell density of 1 x $10^6$ cells/ml in 500 ml shaker flasks. Cells were harvested 96 hours post-infection and separated from supernatant by low speed centrifugation for 10 minutes at 2000 x g at room temperature. For purification of cH6 protein, the supernatant was collected and incubated with Ni-NTA resin (Qiagen) for 2 hours at 4°C. The slurry was loaded on columns and washed trice with washing buffer (50 mM Na2HCO3, 300 mMNaCl, 20 mM Imidazole, pH 8). Protein was eluted in 0.5 ml steps with elution buffer (50 mM Na2HCO3, 300 mMNaCl, 250 mM Imidazole, pH 8), tested for protein content with Bradford reagent and fractions containing protein were pooled. Protein purity and identity was tested by SDS-PAGE, Coomassie staining and Western blot. Protein concentration was determined with Bradford reagent.

#### 6.3.1.4 Mouse experiments

**[00473]** For all procedures, mice were anesthetized with intraperitoneal injections of 0.1 mL of ketamine/xylazine mixtures (1.5 mg ketamine and 0.3 mg xylazine).

**[00474]** Mouse 50% lethal doses ($LD_{50}$) were determined in BALB/c mice (Charles River Laboratories) by infecting groups of four mice with 10-fold serial dilutions of influenza virus. Body weights were monitored for a two week period. Mice that lost greater than 25% of their body weight were considered to have reached experimental endpoint and were euthanized. $LD_{50}$ values were calculated by the method of Reed and Meunch (see Reed and Meunch. 1938, Am. J. Hyg. 27:493-497).

**[00475]** For experiments to assess the stem antibodies produced following A/California/04/09 (Cal/09) virus infection, female, 8-10 week old BALB/c mice were first primed with intramuscular administration of 80 μg of an expression plasmid encoding full length HA from PR8 virus, coupled with the application of electrical stimulation as previously described (TriGrid delivery system, Ichor Medical Systems) (see, e.g., Luxembourg et al., 2007, Expert Opinion on Biological Therapy 7:1647-64). Three weeks later, mice were boosted with a sublethal dose of $10^4$ PFU Cal/09 in a 50 μl volume, intranasally. Control animals either received DNA alone or Cal/09 virus alone, or intramuscular injection of the 2009-2010 vaccine (Cal/09 split vaccine). Three weeks post boost, or the equivalent time point for control animals, mice were bled and sera was harvested to test reactivity to cH6 by immunofluorescence as described below.

**[00476]** For experiments testing the efficacy of cH9 virus as a vaccine construct, PR8 full length DNA was administered as described above. Three weeks post prime, mice were inoculated with $10^3$ PFU of cH9 virus instilled intranasally. Control animals either received DNA alone or Cal/09 virus alone or purified inactivated PR8 virus intramuscularly. Three weeks post boost, or the equivalent time point for control animals, mice were challenged with intranasal inoculation of 5 x $10^4$ $LD_{50}$ of PR8 virus. Mice were weighed for 14 days post challenge. Animals that lost more than 27.5% of their initial body weight were euthanized and scored as dead.

#### 6.3.1.5 Immunofluorescence to confirm expression of chimeric hemagglutinin

**[00477]** Confluent monolayers of 293T cells were transfected with 1 μg of pDZ cH6 plasmid. At 48 hours post transfection, cells were fixed and blocked with 1% bovine serum albumin in PBS containing 0.1% Tween 20. Cells were then incubated with sera pooled from the animals of each of the four experimental groups described above (PR8 DNA alone, Cal/09 alone, PR8 DNA and Cal/09 infection, or Cal/09 split vaccine alone). After three washes with PBS containing 0.1% Tween 20, cells were incubated for 1 hour with Alexa Fluor 488-conjugated anti-mouse IgG (Invitrogen). Infected cells were analyzed by fluorescence microscopy with an Olympus IX70 microscope.

#### 6.3.1.6 ELISA

**[00478]** Ninety-six well ELISA plates (Nunc, MaxiSorp) were coated with 50 ml of baculovirus-expressed cH6 and incubated overnight at 4°C. Plates were blocked 3% milk/PBS and then washed with PBS/0.1% Tween (PBST). Serum from vaccinated mice was serially diluted in PBS and added to the plate, followed by a 1 hour incubation at 37°C. Plates were then washed with PBST and incubated with 1:2500 dilution of horseradish peroxidase linked anti-mouse IgG (GE Healthcare). Following an additional wash with PBST, SigmafastOPD substrate (Sigma) was added. The reaction was stopped with 3M $H_2SO_4$ and optical density measurements were taken at 490 nm.

### 6.3.2 Results

#### 6.3.2.1 Chimeric influenza virus hemagglutinin polypeptides can be used in diagnostic applications

**[00479]** A chimeric hemagglutinin construct comprising the globular head domain from the hemagglutinin of an H6 influenza virus subtype and stem/stalk domain from the hemagglutinin of the PR8 virus was generated to serve as analytical tool to assay production of antibodies by the immunized mice against the H6 stem domain. Because the immunized mice were only exposed to the globular head of H1 viruses, antibodies that were generated in the experimental animals would only be reactive to chimeric H6 hemagglutinin (cH6) if they were directed towards its H1 stem.

**[00480]** As shown in Figures 11A and 11D, treatment with DNA alone or pandemic split vaccine did not elicit any stem reactive antibodies in the vaccinated mice. Conversely, infection with Cal/09 alone generated stem reactive antibodies (Figure 11B), though not to the extent elicited by DNA electroporation and infection (Figure 11C). A cross-reactive H1 stem antibody, C179, was used as a control for the transfection (Figure 11E). As expected, PY102, an antibody directed against the globular head of PR8, did not react to the transfected cH6 HA (Figure 11F).

**[00481]** As shown in Figure 13, the utility of the cH6 chimeric influenza virus hemagglutinin polypeptide as a tool in which to detect stem antibody binding was confirmed by ELISA.

#### 6.3.2.2 Chimeric influenza virus hemagglutinin polypeptides can be used in vaccines

**[00482]** As shown in Figure 12, animals that were vaccinated with inactivated PR8 virus were protected from lethal challenge, while animals that received DNA alone completely succumbed to infection by day 5 post challenge. Animals that received cH9 virus alone also were not protected from infection, with only a 25% survival rate. By contrast, animals that were first primed with DNA and then boosted with cH9 virus were protected from challenge, with a survival rate that was statistically the same as animals vaccinated with the inactivated virus preparation.

## 6.4 EXAMPLE 4: HEMAGGLUTININ STALK ANTIBODIES ELICITED BY INFECTION WITH THE 2009 PANDEMIC H1N1 INFLUENZA VIRUS

**[00483]** This example describes chimeric influenza virus hemagglutinin polypeptdies that were used to study stem domain specific antibodies. Using these polypeptides, it was determined that infection with the 2009 pandemic H1N1 virus elicited a boost in titer of virus-neutralizing antibodies directed against the hemagglutinin stem. In addition to the chimeric influenza virus

hemagglutinin polypeptdies, assays that can be used to measure influenza virus-neutralizing antibodies which are not detected in the traditional hemagglutination-inhibition assay are also described.

### 6.4.1 Materials and Methods

#### 6.4.1.1 Cells and plasmids

**[00484]** 293T and MDCK cells were obtained from ATCC and were maintained in Dulbeccos's Modified Eagle's medium (DMEM) and Minimal Essential Medium (both from Gibco), respectively, each supplemented with 10% fetal calf serum (HyClone), and 100 units/ml of penicillin-100 μg/ml of streptomycin (Pen/Strep, Gibco). TNM-FH media (Gemini Bioproducts) supplemented with 10% fetal calf serum and Hyclone SFX insect culture media (ThermoScientific) were used for Sf9 and BTI-TN5B1-4 (High Five) cell culture.

**[00485]** Chimeric hemagglutinin (cHA) constructs with the stalk of A/Puerto Rico/8/1934 (PR8) containing the globular head domain from either A/Mallard/Sweden/81/02 (cH6/1) virus or A/Guinea fowl/Hong Kong/WF10/99 (cH9/1) viruses were generated using methods previously described (Hai *et al.*, 2008, *J Virol* 82, 10580; Fodor *et al.*, 1999, *J Virol* 73, 9679). Briefly, different components of the chimeric hemagglutinin (cHA) were amplified by PCR with primers containing Sap I sites, digested with Sap I, and cloned into the Sap I sites of the pDZ plasmid (Quinlivan *et al.*, 2005, *J Virol* 79, 8431). For generation of the baculo-transfer plasmids, cH6/1 and cH9/1 were amplified by PCR, cut with BamHI and NotI, and cloned in frame into a modified pFastBac (Invitrogen) baculo-transfer vector that harbors a C-terminal T4 phage foldon and a 6-his tag (Meier *et al.*, 2004, *J Mol Biol* 344, 1051). The sequences of all plasmids were confirmed by Sanger sequencing.

#### 6.4.1.2 Recombinant baculovirus generation, protein expression and purification

**[00486]** In order to generate recombinant cH6/1 and cH9/1 protein, baculo-transfer vectors were transformed into *E. coli* strain DH10Bac (Invitrogen) according to the manufacturer's instructions. DH10Bac colonies showing the right phenotype were picked, grown up and bacmids were prepared using a Plasmid Midi Kit (Qiagen).

**[00487]** Bacmids carrying the cH6/1 or cH9/1 genes were transfected into Sf9 cells with Cellfectin II (Invitrogen) according to the manufacturer's instructions. Recombinant baculovirus

was amplified in Sf9 cells grown in TNM-FH medium (Gemini Bioproducts, West Sacramento, CA) and titers were determined by plaque assay (King *et al.*, 2007, *Methods Mol Biol* 388, 77).

**[00488]** High Five cells grown in HyClone SFX insect cell media (Thermo Fisher Scientific) were infected with recombinant baculovirus expressing cH6/1 or cH9/1 at a multiplicity of infection (MOI) of 10 and a cell density of $1x10^6$ cells/ml in 500 ml shaker flasks (Krammer *et al.*, 2010, *Mol Biotechnol* 45, 226). Cells were harvested 96 hours post infection and separated from supernatant by low speed centrifugation for 10 minutes at 2000g and room temperature. For purification of cHA proteins, the supernatant was collected and incubated with Ni-NTA resin (Qiagen) for 2 hours at 4°C. The slurry was loaded onto columns and washed 3X with washing buffer (50 mM Na2HCO3, 300 mM NaCl, 20 mM imidazole, pH 8). Protein was eluted in 0.5 ml steps with elution buffer (50 mM $Na_2HCO_3$, 300 mM NaCl, 250 mM imidazole, pH 8), tested for protein content with Bradford reagent and fractions containing protein were pooled. Pooled fractions were buffer exchanged in PBS and concentrated using an Amicon Ultra centrifugal filter unit (Millipore) with a 10 kD molecular weight cut-off in a swinging bucket rotor. Protein purity and identity were tested by SDS-PAGE, Coomassie staining and Western blot. The following antibodies were used to confirm expression of cHA: Anti-H6 goat antiserum (BEI, #NR-663), G1-26 (anti-H9, mouse; BEI# NR-9485), 3951 (rabbit, anti-HA2 PR8) (Graves *et al.*, 1983, *Virology* 126, 106), PY102 (anti-PR8 head, mouse), and 12D1 (anti-H3 stalk, mouse) (Wang *et al.*, 2010, *PLoS Pathog* 6, e1000796). Final protein concentrations were determined with Bradford reagent.

#### 6.4.1.3 Rescue of recombinant cHA expressing viruses

**[00489]** In order to rescue the recombinant virus expressing cH9/1, reverse genetics plasmids that encode vRNA and mRNA of the six wild type viral segments from PR8, as well as plasmids encoding the N3 NA from A/mallard/Alberta/24/01 virus and cH9/1 were used, as previously described (Hai *et al.*, 2008, *J Virol* 82, 10580; Fodor *et al.*, 1999, *J Virol* 73, 9679, *27*). Briefly, 293T cells were transfected with 1 μg of each of the eight plasmids using Lipofectamine 2000 (Invitrogen) according to the manufacturer's instructions. At 12 hours post transfection, the medium was replaced with DMEM containing 0.3% bovine serum albumin, 10 mM HEPES, and 1.5 μg of TPCK (l-1-tosylamide-2-phenylethyl chloromethyl ketone)-treated trypsin/mL (Sigma T1426). At two days post transfection, virus-containing supernatant was inoculated into 10-day-old embryonated chicken eggs. Allantoic fluid was harvested after 2 days of incubation at 37° C

and assayed for the presence of virus by the hemagglutination of chicken red blood cells. The rescued cH9/1 virus was then propagated in 10 day old eggs following a 48 hour incubation at 37°C. Virus stocks were titered by plaque assay as previously described on MDCK cells in the presence of TPCK trypsin (Steel *et al.*, 2009, *J Virol* 83, 1742). The sequence of the cH9/1 RNA was confirmed by sequencing of reverse transcription-PCR products.

**6.4.1.4 Immunofluorescence to confirm expression of chimeric hemagglutinin**

**[00490]** Confluent monolayers of MDCK cells were infected with cH9/1N3 virus at an MOI of 2. At 48 hours post infection, cells were fixed and blocked with 1% bovine serum albumin in PBS containing 0.1% Tween 20. Cells were then incubated with mouse mAbs: anti-NP antibody HT103, PY102, anti-H9 (BEI NR#9485), or a pan-H1 stalk-specific antibody (6F12). After three washes with PBS containing 0.1% Tween 20, cells were incubated for 1 hour with Alexa Fluor 488-conjugated anti-mouse IgG (Invitrogen). Infected cells were analyzed by fluorescence microscopy with an Olympus IX70 microscope.

**6.4.1.5 Human serum samples**

**[00491]** Human sera samples were collected and used in accordance with insitututional protocols. Sera were collected from three patient cohorts: adults not infected with pH1N1, children not infected with pH1N1, and pH1N1 virus infected adults. Sera were collected from pH1N1 infected patients within the first 3 weeks of symptomatic infection. For experiments using pooled serum, an equal volume of each sample was mixed to generate pool. Confirmation of infection was performed by Wrammert et al. by RT-PCR and by serological assays (*Wrammert et al., 2011, J Exp Med* 208, 181-193).

**6.4.1.6 Hemagglutinin inhibition assays**

**[00492]** Collected sera were first inactivated by trypsin-heat-periodate treatment or by RDE treatment in order to remove non-specific inhibitors of hemagglutination (Coleman, Dowdle, 1969, *Bull World Health Organ* 41, 415 (1969). Hemagglutination inhibition (HI) assays were performed to test reactivity with cH9/1N3 and A/duck/France/MB42/76 (H6 HA) (Desselberger *et al.*, 1978, *Proc Natl Acad Sci U S A* 75, 3341 (Jul, 1978)) viruses as previously described (Lowen *et al.*, 2009,. *J Virol* 83, 2803). A sample is considered negative if HI activity is not seen with a 1:10 dilution of the serum.

**6.4.1.7 ELISAs**

**[00493]** Ninety-six well ELISA plates (Qiagen HisSorb or Nunc Immulon 2) were coated with 50 ul of baculovirus-expressed cH6/1, cH9/1 or full length hemagglutinin (H5 HA, BEI NR#660; H3 HA, BEI NR#15171) proteins or H1 sequence (PR8) long alpha helix (LAH) (Wang *et al.*, 2010, *Proc Natl Acad Sci U S A* 107, 18979) diluted in PBS and incubated overnight at 4°C. Plates were blocked with 0.5% milk/2% goat sera/PBS and then washed 3X with PBS/0.1% Tween (PBST). Monoclonal antibodies, sera from human subjects, and mouse sera used as controls were serially diluted in PBS or blocking buffer and then added to the plate, followed by a one hour incubation at room temperature. Plates were then washed 3X with PBST and incubated with 1:5000 dilution of goat anti-Human IgG [Fc] coupled to alkaline phosphatase (AP) (Meridian Life Science) or anti-mouse AP (Invitrogen) for an additional hour. Following washing 3X with PBST, p-nitrophenyl phosphate substrate (Sigma) was added. The reaction was stopped with NaOH after 10 minutes and optical density measurements were taken at 405 nm.

**6.4.1.8 Plaque reduction assay**

**[00494]** Sera from adult infected and naïve (not infected with pH1N1 virus) patients were first pooled and loaded onto a gravity flow column with protein G sepharose (GE Healthcare) for purification of IgG proteins. The column was washed with PBS. The polyclonal antibodies were eluted with a 0.1 M glycine buffer (pH 2.7). A 2 M Tris-HCl buffer (pH 10) was added immediately at a 1:10 ratio to restore the pH. The eluate was buffer exchanged in PBS and concentrated using an Amicon Ultra-15 centrifugal filter unit (Millipore) with a 50 kD MW cut-off in a swinging bucket rotor. Protein concentrations were measured on a NanoDrop 2000 spectrophotometer using the A280 method. Removal of non-specific serum inhibitors was confirmed by HI tests using multiple virus strains that demonstrated an absence of HI activity in the purified IgG preparations (data not shown). Neutralization capability of stalk-reactive antibodies was assessed as previously described (Wang *et al.*, 2010, *PLoS Pathog* 6, e1000796). Virus was first diluted to a concentration that would yield 100 plaque forming units per well. Different concentrations of IgG from pooled sera were then co-incubated with virus at room temperature for an hour. Six-well plates seeded with MDCK cells were washed with PBS and then infected with 200ul of virus-IgG mixtures. Following a forty-five minute incubation at 37°C, virus and IgG were aspirated from cells and an agar overlay containing appropriate antibody concentration and TPCK trypsin was added to each well. Plates were incubated for 2

days at 37°C. Plaques were visualized by immunostaining (Bouvier *et al.*, 2008, *J Virol* 82, 10052) using anti-H9 antibody G1-26.

#### 6.4.1.9 Pseudotype particle neutralization assay

**[00495]** The procedure for pseudotype particle production was adapted from previous studies (Evans *et al.*, 2007, *Nature* 446, 801). Briefly, 293-T cells were co-transfected with four plasmids encoding (i) a pro-virus containing the desired reporter (V1-GLuc), (ii) HIV Gag-Pol, (iii) the chimeric cH9/1 hemagglutinin protein and (iv) influenza B/Yamagata/16/88 neuraminidase (NA) (Tscherne *et al.*, 2010, *J Virol Methods* 163, 336). The V1-GLuc plasmid encodes a luciferase protein that is secreted from cells and can be detected in the cell supernatant. Supernatants were collected 48 h post-transfection and subsequently filtered (0.45 μm pore size) in order to purify the cH9/1 particle preparations. Particles were then incubated (at quantity determined to give luciferase activity within the linear range after infection) with different concentrations (50μg/ml, 10μg/ml and 2μg/ml) of purified human IgGs and were added to MDCK cells. Infections proceeded for 6 hours before cells were washed and fresh supernatant was placed over cells. All infections using pseudotype particles were performed in the presence of 1 μg/ml polybrene (Sigma, St. Louis, MO) (Tscherne *et al.*, 2010, *J Virol Methods* 163, 336). Forty-eight hours post-infection luciferase assays were performed.

### 6.4.2 Results

#### 6.4.2.1 Development of chimeric hemagglutinin-based reagents

**[00496]** Chimeric hemagglutinin (cHA) constructs were generated to serve as analytical tools to assess the presence of stalk antibodies in human sera. By taking advantage of a disulfide bond that exists between C52 and C277, and that delineates the boundary between the HA stalk and head, expression plasmids were engineered that encode the globular head domain of an H6 or H9 hemagglutinin atop the stalk domain from the HA of PR8 virus (Fig. 14A). It was hypothesized that human serum samples containing stalk antibodies would likely be negative for hemagglutination inhibition (HI) activity against H6 or H9 viruses (due to lack of prior exposure to these virus subtypes), yet would be reactive with the cH6/1 or cH9/1 constructs due to prior exposure to the H1 hemagglutinin stalk. These tools, recombinantly expressed cHA proteins and viruses expressing the cHAs, could be used to assess relative amounts of stalk antibodies in

human serum samples and to measure any neutralizing activity mediated by those stalk-specific antibodies.

**[00497]** In order to generate cH6/1 and cH9/1 protein for analytical assays, plasmids coding for the chimeric HAs were generated and expressed as soluble proteins in a baculovirus expression system. Coomassie staining of 2μg of total protein suggests a high degree of purity in these preparations (Fig. 17A). The slight delayed migration of cH9/1 is thought to be the result of an increased number of occupied glycosylation sites on the cH9/1 head. The cHA proteins were further characterized by western blot analysis using antibodies reactive with various parts of the HA. As shown in Fig. 17B, only cH6/1, cH9/1 and full length HA from PR8 reacted with a rabbit polyclonal antiserum specific for the PR8 stalk. Monoclonal antibodies against the head domains of H6, H9, and PR8 confirmed that the chimeric constructs were expressing exotic heads atop a PR8 stalk. H3 protein was used as a negative control, and was only detected when using the pan-H3 antibody 12D1 (Wang *et al.*, 2010, *PLoS Pathog* 6, e1000796).

**[00498]** Recombinant viruses expressing the chimeric molecules were also rescued for the purpose of detecting neutralizing stalk antibodies. Because all human influenza viruses over the last century have encoded NA of the N1 or N2 subtype, it was reasoned that the rescue of the cH9/1N3 reassortant virus would allow for the assessment of the neutralizing capability of stalk-specific antibodies, while not measuring any (N1 or N2) neuraminidase antibody activity. The cH9/1N3 virus (expressing the H1 stalk with H9 globular head HA with an N3 subtype neuraminidase) was rescued using reverse genetics and grown to high titers in embryonated chicken eggs. The plaque assay phenotype of this virus was similar to that of PR8 wild type virus (Fig. 14C). To confirm the presence of the H9 head after virus passage, cells were infected with cH9/1N3 virus. Infected cells were then probed with mouse mAb G1-26, an antibody specific for H9 subtype hemagglutinin proteins. A pan-H1 stalk specific antibody, 6F12, was used to detect both wild type PR8 and cH9/1N3 virus infected cells (Fig. 14B).

#### 6.4.2.2 Stalk specific antibodies bind and neutralize cHA

**[00499]** In order to confirm that cH6/1 and cH9/1 proteins could be used as tools to detect stem antibodies, the use of these cHAs was first validated with an antibody known to react with the HA stalk. Indeed, mouse mAb C179, an antibody reactive with the stalk of H1 HA (Okuno *et al.*, 1993, *J Virol* 67, 2552), bound to baculovirus expressed cH6/1 and cH9/1 protein by ELISA in a dose dependent manner (Figs. 18A and B).

**[00500]** Next, it was ascertained whether replication of the cH9/1N3 virus could be inhibited by monoclonal antibody 6F12, which has neutralizing activity against H1 influenza viruses (data not shown). Antibody 6F12 was able to bind and neutralize cH9/1N3 virus in a plaque reduction assay (Figs. 18 C and D), in a dose dependent manner, with one hundred percent inhibition seen at concentrations above 4μg/ml. These results validated the hypothesis that the chimeric proteins and the recombinant cH9/1N3 virus could be used to detect stalk antibodies with neutralizing activity.

#### 6.4.2.3 Patients infected with pH1N1 have high titers of antibodies that bind and neutralize cHA

**[00501]** Prior to the use of cH6/1 and cH9/1 soluble proteins to quantitate stalk-reactive antibodies in patient blood samples, the sera for HI activity was tested against viruses expressing these two HA subtypes. Using A/duck/France/MB42/76 (H6) and cH9/1N3 viruses, it was confirmed that all adult and pediatric serum samples collected were HI negative (results not shown).

**[00502]** Next, the reactivity of the sera with cH6/1 and cH9/1 proteins was tested by ELISA. Sera collected from adult and pediatric subjects not infected with pH1N1 viruses showed little reactivity with either protein. However, sera collected from patients infected with pH1N1 influenza virus showed enhanced binding to both cHA constructs, with a greater than 30-fold difference in IgG reactivity (comparing dilutions that yield equivalent optical density readings) when comparing serum pools from pH1N1 infected with those of uninfected adults and children (Figs. 15 A and B). It was therefore reasoned, by taking the negative HI data into account, that reactivity with cHA proteins is occurring in the stalk domain.

**[00503]** Using pooled samples of human sera, IgG binding to a portion of the HA stem, the long alpha helix (LAH), was also tested. These IgGs had previously been shown to mediate protective immunity in mice (Wang *et al.*, 2010, *Proc Natl Acad Sci U S A* 107, 18979). Sera from patients infected with pH1N1 contained antibody reactive with the H1 LAH, whereas patients unexposed to the pandemic virus had minimal LAH-specific serum antibody (Fig. 15C).

**[00504]** The H5 hemagglutinin subtype is within the same phylogenetic group as the H1 HA, and shares a very similar stalk structure (Ekiert *et al.*, 2009, *Science* 324, 246). Interestingly, patients exposed to the pH1N1 had boosted serum antibody specificities reactive with the H5 protein (Fig. 15D), while not having any serum HI activity against the homologous H5 subtype

virus (data not shown). This result suggested that exposure to the pH1N1 virus may have conferred a degree of anti-H5 immunity mediated by stalk-specific antibodies.

**[00505]** Importantly, patients infected with pH1N1 did not have boosted serum antibody specific for an H3 hemagglutinin protein (H3 being in a separate phylogenetic group from H1 and H5 HAs) (Fig. 15E). This result demonstrates that the enhanced titer of stalk-specific antibodies in sera from pH1N1-infected patients is not a function of general immune stimulation; rather, the H1 stalk antibody specificities were selectively boosted by infection with the pandemic virus strain.

**[00506]** Next, it was assessed whether these stalk reactive antibodies found in these human samples had neutralizing capability. Serum samples from infected and uninfected adults were pooled and total IgG was purified in order to remove non-specific inhibitors (eg: sialic acid containing molecules and lectins) that would bind to the hemagglutinin head. Using these pure IgG preparations, complete inhibition plaque formation at antibody concentrations above 55.5μg/mL total serum IgG (Figs. 16 A and B) was achieved. In accordance with the ELISA data, an approximately 30-fold difference in neutralizing capability was observed when comparing sera from pH1N1 infected with those of uninfected adults. Using mAb 6F12 as a standard, a comparison was able to be made between neutralizing activities mediated by 6F12 and the polyclonal human IgG preparation. By comparing the concentrations of 6F12 and human IgGs that yielded 100% neutralization of cHA virus, it was estimated that 7% of total human IgG from patients infected with pH1N1 during the last 30 days comprised neutralizing stalk antibodies.

**[00507]** Finally, the neutralizing capability of stalk reactive antibodies was evaluated, using a pseudotype particle infection assay that has a read-out of luciferase activity which is generated upon virus entry into host cells. Pseudotyped particles expressing the cH9/1 protein were incubated with purified human IgG and neutralizing activity was measured by inhibition of particle entry resulting in absence of luciferase enzymatic activity in cell supernatants (see methods). Consistent with the plaque reduction assay, the pseudotyped particle assay also showed 100% neutralization of particles at total IgG concentrations of exceeding 10μg/ml (Fig. 16C).

### 6.4.3 Conclusion

**[00508]** Novel analytical tools, in the form of chimeric hemagglutinin proteins and viruses expressing those chimeric proteins, were developed that allowed for the selectively detection of stalk-specific antibodies in preparations that also include antibodies that bind the globular head of hemagglutinin proteins. These novel hemagglutinin constructs have a constant H1 subtype stalk, with globular head domains from distinct hemagglutinin subtypes (ex: H1 stalk with H6 head). This was accomplished by taking advantage of a disulfide bond that exists between cysteines 52 and 277 in the hemagglutinin protein (19) to exchange the intervening sequence with that of a different HA subtype.

**[00509]** Using these chimeric hemagglutinin (cHA) constructs, it was demonstarted that a small cohort of humans with confirmed pH1N1 virus infection generated a high titer of stalk specific, neutralizing antibodies compared to uninfected adult and pediatric controls not infected with pH1N1 viruses. These findings support the hypothesis that antibodies reactive with the hemagglutintin stalk, generated in response to pH1N1 infection, likely contributed to the dying out of seasonal H1N1 viruses that were circulating prior to the influenza pandemic of 2009.

## 6.5 EXAMPLE 5: INFLUENZA VIRUSES EXPRESSING CHIMERIC HEMAGGLUTININS: GLOBULAR HEAD AND STALK DOMAINS DERIVED FROM DIFFERENT SUBTYPES AND PHYLOGENIC GROUPS

**[00510]** This example describes several functional chimeric influenza virus hemagglutinins encompassing a variety of globular head and stalk combinations from different hemagglutinin subtypes and different phylogenic groups as wells as recombinant influenza viruses expressing these chimeric hemagglutinins, which had growth properties similar to those of wild-type influenza viruses. These chimeric recombinant viruses possess growth properties similar to those of wild-type influenza viruses and can be used as reagents to measure domain-specific antibodies in virological and immunological assays.

### 6.5.1 Materials and Methods

#### 6.5.1.1 Cells and viruses

**[00511]** 293T and MDCK cells were obtained from the American Type Culture Collection (ATCC) and were maintained either in Dulbecco's minimal essential medium (DMEM) or in MEM (Gibco, Invitrogen) supplemented with 10% fetal calf serum (HyClone; Thermo

Scientific) and penicillin-streptomycin (Gibco, Invitrogen). The A/Puerto Rico/8/1934 (PR8) and A/Perth/16/2009 (Perth/09) wild type (kindly provided by Alexander Klimov, CDC) and recombinant viruses were grown in 10-day old specific pathogen-free embryonated hen's eggs (Charles River) at 37°C for 2 days.

**6.5.1.2 Construction of plasmids.**

**[00512]** Plasmids encoding the different chimeric hemagglutinins were constructed using a strategy similar to what has been previously described (*see, e.g.*, Fodor *et al.*, 1999, J *Virol* 73:9679-9682; and Hai *et al.*, 2008, *J Virol* 82:10580-10590). Briefly, the different segments of chimeric HA were amplified by PCR with primers containing *Sap*I sites, digested with *Sap*I, and cloned into the *Sap*I sites of the ambisense expression vector pDZ vector in which vRNA transcription is controlled by the human RNA polymerase I promoter and the mouse RNA polymerase I terminator, and mRNA/cRNA transcription is controlled by the chicken beta actin polymerase II promoter (*see, e.g.*, Quinlivan et al., 2005, *J Virol* 79:8431-8439), through multi-segmental ligation. We kindly thank Daniel Perez (University of Maryland) for the H7 HA plasmid (Genbank ID: DQ017504). The plasmids encoding A/Puerto Rico/8/1934 (PR8) genes were used as previously described (Hai *et al.*, 2008, *J Virol* 82:10580-10590).

**6.5.1.3 Nucleotide sequence accession number**

**[00513]** All constructed cHA genes used in this study have been deposited in the Influenza Research Database under the accession number IRD-RG-684014, IRD-RG-684022, IRD-RG-684030, and IRD-RG-684038. The chimeric cH1/1, cH5/1, cH7/3 and cH5/3 are listed as A/Puerto Rico/8-RGcH1-1/34, A/Puerto Rico/8-RGcH5-1/34, A/Perth/16-RGcH7-3/09, and A/Perth/16-RGcH5-3/09, respectively.

**6.5.1.4 Flow cytometric analysis**

**[00514]** To assess levels of hemagglutinin protein expression at the cell surface, 293T cells were transfected with 1 μg of the appropriate plasmid using Lipofectamine 2000 (Invitrogen) according to the manufacturer's instructions or MDCK cells were infected with cHA-expressing recombinant viruses. At 48 h post-transfection, 293T cells were trypsinized and resuspended in PBS containing 2% FBS prior to staining with the monoclonal antibody (mAb) 6F12 (5μg/ml), a mAb generated in our laboratory that is broadly reactive to the stalk domain of group 1 HAs (data not shown) or with the mAb 12D1 (5μg/mL) against H3 HAs (see Wang *et al.*, 2010, *PLoS*

*Pathog* 6:e1000796). At 12 h post-infection, MDCK cells were resuspended by trypsinization and stained with the mAb 12D1. Stained cells were analyzed on a Beckman Coulter Cytomics FC 500 flow cytometer, and the results were analyzed using FlowJo software.

#### 6.5.1.5 *Pseudoparticle generation and entry assay*

**[00515]** The procedure for pseudoparticle production was adapted from previous studies (*see, e.g.*, Evans *et al.*, 2007, *Nature* 446:801-805 and Tscherne *et al*, 2010, *J Virol Methods* 163:336-43). Briefly, we co-transfected 293T cells with four plasmids encoding (i) a pro-virus containing the desired reporter (V1-Gaussia luciferase) (Evans *et al.*, 2007, *Nature* 446:801-805), (ii) HIV Gag-Pol (Evans *et al.*, 2007, *Nature* 446:801-805), (iii) chimeric hemagglutinin protein and (iv) B/Yamagata/16/88 virus neuraminidase (NA). Supernatants were collected 72 h post-transfection and subsequently filtered (0.45 μm pore size). The presence of pseudotype virus like particles (VLPs) was evaluated through hemagglutination assay. Different VLP preparations were adjusted to the same 4 hemagglutination units prior to inoculation of MDCK cells. All of the following assays using pseudoparticles were performed in the presence of 1 μg/mL polybrene (Sigma) to increase the efficiency of transduction (*see, e.g.*, Evans *et al.*, 2007, *Nature* 446:801-805 and Tscherne *et al*, 2010, *J Virol Methods* 163:336-43).

**[00516]** The entry assay was performed by transducing MDCK cells with pseudoparticles that expressed different chimeric hemagglutinins and contained the *Gaussia* luciferase reporter. Twenty-four hours post-transduction, cells were washed three times with fresh medium to remove any residual *Gaussia* luciferase protein present in the inoculum. Forty-eight hours post-transduction, luciferase assays were performed (Evans *et al.*, 2007, *Nature* 446:801-805).

#### 6.5.1.6 *Rescue of recombinant chimeric influenza A viruses*

**[00517]** Rescue of influenza A viruses from plasmid DNA was performed as previously described (*see, e.g.*, Fodor *et al.*, 1999, *J Virol* 73:9679-9682; and Hai *et al.*, 2008, *J Virol* 82:10580-10590). To generate the recombinant wild-type (rWT) PR8 virus, 293T cells were co-transfected with 1 μg of 8 pDZ PR8 rescue plasmids using Lipofectamine 2000 (Invitrogen). The wild type HA plasmid was substituted with a plasmid encoding the desired chimeric HA in order to generate cHA-expressing recombinant viruses. At 6 h post-transfection, the medium was replaced with DMEM containing 0.3% bovine serum albumin (BSA), 10 mM HEPES, and 1.5 μg/ml TPCK (L-1-tosylamide-2-phenylethyl chloromethyl ketone)-treated trypsin (Sigma).

After 24 hours post-transfection, 8-day old embryonated chicken eggs were inoculated with virus-containing supernatant. Allantoic fluid was harvested after 2 days of incubation at 37°C and assayed for the presence of virus by hemagglutination of chicken red blood cells. Virus stocks were titered by plaque assay on MDCK cells as previously described (Fodor *et al.*, 1999, *J Virol* 73:9679-9682, *Hai et al., 2008, J Virol* 82:10580-10590).

**6.5.1.7 *Virus growth kinetics assay***

**[00518]** To analyze the replication characteristics of recombinant viruses, 10-day old embryonated chicken eggs were inoculated with 100 plaque forming units (pfu) of wild-type or cHA-expressing recombinant viruses. Allantoic fluid was harvested and subsequently assayed for viral growth at 0, 9, 24, 48, and 72 h post-infection (hpi). The titers of virus present in allantoic fluid were determined by plaque assay on MDCK cells as referenced above.

**6.5.1.8 *Immunostaining of plaques***

**[00519]** Plaques were visualized by immunostaining with mAb HT103 against the influenza A nucleoprotein (NP), using a protocol that has been previously described (Bouvier *et al.*, 2008, *Journal of Virology* 82:10052-8; and Steel *et a.l*, 2009, *J Virol* 83:1742-53).

**6.5.1.9 *Western blot and indirect immunofluorescence analysis***

**[00520]** Confluent MDCK cells were infected (multiplicity of infection [MOI] of 2) with indicated recombinant influenza viruses or mock infected with phosphate-buffered saline (PBS) for 1 h at 37°C. At 12 hpi, cells were lysed in 1X SDS loading buffer as described previously (*see, e.g.*, Hai et al., 2008, *J Virol* 82:10580-10590). The reduced cell lysates were analyzed by Western blot analysis using monoclonal antibodies (mAbs) against influenza A virus nucleoprotein (NP) (HT103), PR8 HA head domain (PY102), Cal/09 HA head domain (29E3), VN/04 HA head domain (mAb #8) and 12D1, a pan-H3 antibody reactive against the HA stalk. In order to detect H7 head domains, polyclonal goat sera NR-3152 was used (raised against A/FPV/Dutch/27 (H7) virus, BEI Resources). An anti-glyceraldehyde 3-phosphate dehydrogenase (GAPDH) antibody (Abcam) was used for the loading control. Proteins were visualized using an enhanced chemiluminescence protein detection system (PerkinElmer Life Sciences).

**[00521]** For immunofluorescence analysis, confluent monolayers of MDCK cells on 15-mm coverslips were infected with recombinant viruses at an MOI of 2. At 15 hpi, cells were

fixed and permeabilized with methanol-acetone (ratio, 1:1) at -20°C for 20 minutes. After being blocked with 1% bovine serum albumin in PBS containing 0.1% Tween 20, cells were incubated for 1 h with the antibodies described above, as well as mAb 6F12. After three washes with PBS containing 0.1% Tween 20, cells were incubated for 1 h with Alexa Fluor 594-conjugated anti-mouse IgG (Invitrogen) or Alexa Fluor 594-conjugated anti-goat IgG (Invitrogen). Following the final three washes, infected cells were analyzed by fluorescence microscopy with an Olympus IX70 microscope.

#### 6.5.1.10 *Plaque reduction assay*

**[00522]** Plaque reduction assay was performed as previously described (*see* Wang *et al.*, 2010, *PLoS Pathog* 6:e1000796). Approximately 60 to 80 pfu of recombinant viruses expressing cHA made up of Cal/09 or VN/04 globular head domains atop a PR8 stalk were incubated with or without different concentrations (100, 20, 4, 0.8, 0.16 and 0.032 ug/ml) of mAb KB2, a broadly neutralizing anti-HA stalk antibody generated in our laboratory (data not shown) for 60 minutes in a total volume of 240 uL at room temperature. A confluent layer of MDCK cells in 6-well plates was washed twice with PBS and then incubated with the antibody-virus mixture for 40 minutes at 37°C. A TPCK-trypsin agar overlay supplemented with antibody at the above-described concentrations or no antibody was then added to each well after the inoculum had been aspirated off. Plates were incubated for 2 days at 37°C. Plaques were then visualized by immunostaining (Bouvier *et al.*, 2008, *Journal of Virology* 82:10052-8; and Steel *et a.l*, 2009, *J Virol* 83:1742-53) with anti-influenza A NP antibody HT103.

#### 6.5.1.11 *Pseudotype particle neutralization assay*

**[00523]** The procedure for pseudotype particle production was the same as described above, using the cHA construct that is comprised of either a VN/04 (H5) or a Cal/09 (H1) head and a PR8 (H1) stalk with the influenza B/Yamagata/16/88 virus NA. Particles were then incubated with different concentrations of mAb KB2 at 5 fold dilutions from 100 to 0.032 μg/mL. Then, these mixtures were added to MDCK cells. Transductions proceeded for 6 hours before cells were washed and fresh medium was placed over cells. All transductions using pseudotype particles were performed in the presence of 1 μg/mL polybrene (Sigma, St. Louis, MO) (Tscherne *et al*, 2010, *J Virol Methods* 163:336-43). Forty-eight hours post-transduction,

luciferase assays were performed in order to assay the degree in which entry was blocked by mAb KB2.

### 6.5.2 Results:

#### 6.5.2.1 Generation of chimeric hemagglutinins

**[00524]** In order to see if the cysteine residues forming the Cys52-Cys277 disulfide bond were conserved, an alignment of influenza A virus HA sequences of the H1, H3, H5 and H7 subtypes were used in this study. Because these cysteine residues are highly conserved across HA subtypes, for both group 1 and group 2 HAs, the Cys52-Cys277 disulfide bond was used as a delineating point between the head and stalk domains. By defining the sequence between Cys52 and Cys277 as the head region, and the remainder of the molecule as the stalk, it was rationalized that constructs could be made that encode novel head and stalk combinations from a variety of HA subtypes (Figs. 19 A and B).

**[00525]** The degree of amino acid identity that exists between the stalk regions of hemagglutinin subtypes further encouraged us that the swapping of head domains might be possible. Higher percentages of amino acid identity were seen in the stalk domains across all subtypes, compared to the head domains (Fig. 20).

**[00526]** All 16 subtypes of influenza HA are classified into two phylogenetic groups (Palese and Shaw, 2006, Orthomyxoviridae: the viruses and their replication, Fields virology, 5th ed., 1647–1690 ). Because higher percentages of amino acid identity was observed within stalk regions of a particular group (Fig. 20), and because one cHA virus that contained head and stalk domains from group 1 viruses had been successfully generated (Pica *et al.*, 2012, *PNAS* 109:2573-8), an attempt was made to generate intra-group cHAs. For group 1, two chimeric hemagglutinin constructs that encode either the pandemic H1 Cal/09 HA or VN/04 globular head domain with the stalk region from PR8 (H1) HA (cH1/1 and cH5/1, respectively) were generated (Fig. 19B). A similar strategy was applied to generate a chimeric HA that expressed head and stalk domains from different group 2 influenza strains: the head from Alb/01 (H7, group 2) and the stalk region from Perth/09 (H3, group 2) HA (cH7/3) (Figure 19B). Finally, it was evaluated whether the head and stalk domains could be swaped to make an inter-group chimeric HA containing the head domain of VN/05 HA (H5, group 1) atop a Perth/09 HA (H3, group 2) stalk (cH5/3) (Fig. 19B).

**[00527]** Following the construction of these plasmids, experiments were performed to determine whether the different chimeric HA constructs could be expressed and transported to the cell surface like wild-type HAs. Fluorescence-activated cell sorter (FACS) analysis of transiently transfected 293T cells was performed following surface staining with H1 and H3 stalk domain specific antibodies, respectively. Using this method, cell surface expression of all four chimeric constructs were detected (Fig. 21). However, compared to the wild type PR8 HA less surface protein expression was detected for the cH1/1 construct, which could be attributed to the inherent character associated with the head domain of the Cal/09 HA or a lower transfection efficiency for this chimeric DNA construct. In addition, it is of note that there were differences in the cell surface expression pattern for the cH7/3 and cH5/3 constructs. This "double peak" expression pattern was observed only in transfection conditions, and was reproducible. It was not detected upon infection with either cH7/3 or cH5/3-expressing recombinant viruses (Fig. 21). Therefore, these data indicate that the cHAs can be transported through the Golgi complex to the cell surface.

**[00528]** Next, the entry characteristics of the different cHAs through transduction of MDCK cells were examined using retroviral pseudotype particles that contained a luciferase reporter construct and expressed the cHA and wild-type B/Yamagata/16/88 virus NA on the particle surface. The entry efficiency mediated by the cHA proteins was detected by the luciferase read-out. Comparable levels of pseudotype particle-mediated luciferase expression were observed for cH5/1, cH7/3 and cH5/3 chimeric HAs and the corresponding wild type proteins (Fig. 22). Particles encoding the cH1/1 HA expressed lower luciferase levels compared to the other HA constructs, which could be due to either the lower expression of the cH1/1 in the producer cell line and hence fewer HA trimers per particle or the less efficient entry properties of the cH1/1 HA. It is also possible that when normalizing the pseudotype particles to 4 hemagglutinin units, the actual amount of pseudotype particles may vary due to differences in binding to red blood cells.

#### 6.5.2.2 Generation of recombinant influenza viruses bearing chimeric hemagglutinins

**[00529]** Because it had determined that our cHA constructs were efficiently expressed and transported to the cell surface, a study was performed to assess whether a recombinant influenza virus that encodes a cHA could be rescued. Viruses containing the different cHAs were

successfully generated using previously published protocols (*see, e.g.*, Fodor *et al.*, 1999, *J Virol* 73:9679-9682; and Hai *et al.*, 2008, *J Virol* 82:10580-10590). The resulting viruses were plaque purified, amplified in 10 day old embryonated eggs and the chimeric segments were analyzed by RT-PCR and sequenced. In all cases, the virus was found to have the expected chimeric HA segment and no other HA segment (data not shown).

**[00530]** The presence of the cHAs in rescued viruses was further confirmed by Western blot (Figure 23) and indirect immunofluorescence of infected cells (Figure 24). MDCK cells were infected with rWT PR8, wild-type Perth/09, cH1/1, cH5/1, cH7/3 and cH5/3 viruses. cH1/1 and cH5/1 chimeric HA proteins were detected in the corresponding samples using antibodies reactive against the head domains of Cal/09 (H1) HA (29E3) (Medina *et al.*, 2010, *Nature Communications* 1:28) or VN/04 (H5) HA (mAb #8) (Steel *et al.*, 2009, *J Virol* 83:1742-53) respectively (Figure 23). Comparable expression levels among the cH7/3, cH5/3 and wild type Perth HA were observed using 12D1, a pan-H3 anti-stalk mAb (*see* Wang *et al.*, 2010, *PLoS Pathog* 6:e1000796). The wild type Perth HA showed a slower migration on the gel that is likely due to a higher number of glycosylation sites in the globular head domain. It was confirmed that the correct HA head domain was expressed atop an H3 stalk by using anti-H7 polyclonal (NR-3152) or anti-H5 monoclonal antibodies (mAb #8) on cH7/3 or cH5/3 infection samples, respectively. Positive bands were detected in both cases.

**[00531]** For the immunofluorescence study, the infection conditions were similar to those used for Western blot analysis. Infected cells were stained with corresponding antibodies as used in Fig. 23. All infected cells showed the expected expression of the chimeric and wild type HAs, as well as of the influenza A virus NP (Fig. 24).

#### 6.5.2.3 Replication characteristics of recombinant viruses

**[00532]** The growth properties of wild type and recombinant viruses were assessed in 10-day-old embryonated chicken eggs at 37°C (Fig. 25A). The rWT PR8 virus was included for comparison of the growth kinetics of the recombinant viruses expressing chimeric HAs. cH5/1 and cH5/3 viruses displayed comparable replication kinetics to that of rWT PR8 virus. cH7/3 virus grew to similar peak titers as rWT PR8 at 48 hpi ($1X10^9$ PFU/mL), though there was a 2 log reduction in viral titer compared to the rWT PR8 virus at 9 hpi. The cH1/1 virus was attenuated as compared to the rWT PR8 virus, as shown by reduced viral titers at all time points.

Nonetheless, cH1/1 virus reached a respectable peak titer of approximately $10^8$ PFU/mL. The Perth/09 Wild type virus grows to comparable peak titers in embryonated eggs (data not shown).

**[00533]** The plaque phenotype of each of the chimeric viruses was also evaluated in MDCK cells. All viruses formed comparable sized plaques as shown in Fig. 25B. These data together confirm that the chimeric HA constructs fold correctly and are biologically functional.

#### 6.5.2.4 Stalk specific antibodies can neutralize cHA-expressing viruses and pseudoparticles

**[00534]** Finally, stalk-specific antibodies were tested for the ability to neutralize our newly generated recombinant viruses expressing cHAs. Plaque reduction assays were performed in the presence of mAb KB2, an HA-stalk specific antibody with broad group 1 reactivity or without antibody. It was shown that mAb KB2 neutralizes all cHA-expressing viruses with similar efficiency and in a dose dependent manner. At 100ug/mL, mAb KB2 was able to completely neutralize cH1/1 and cH5/1 viruses with 100% efficiency, with some neutralizing activity at concentrations as low as 4ug/mL (Fig. 26A).

**[00535]** To confirm these results, a pseudotype particle inhibition assay was performed with mAb KB2. Pseudotype particles expressing cH1/1 or cH5/1 and influenza B virus NA were added to MDCK cells in the presence of mAb KB2, or without antibody. Forty-eight hours post-transduction, supernatant was collected and luciferase activity was analyzed. As expected, mAb KB2 blocked the entry of cH1/1 and cH5/1 pseudotype particles in a dose dependent manner at concentrations above 4ug/mL. While a lower concentration of mAb KB2 was sufficient to inhibit entry of pseudotype particles compared to concentrations used in the plaque reduction assay, this was an expected result due to the assumed lower incorporation of HA trimers on the surface of pseudotype particles (Corti *et al.*, 2010, *The Journal of Clinical Investigation* 120:1663-73). This phenomenon of different neutralizing potencies of mAbs in assays that involve whole virus versus pseudotype particles has been appreciated in other studies (Corti *et al.*, 2010, *The Journal of Clinical Investigation* 120:1663-7321; Sui *et al.*, 2009, *Nature Structural & Molecular Biology* 16:265-73).

### 6.5.3 Conclusion

**[00536]** A novel strategy was developed to generate influenza viruses with chimeric HA proteins bearing different HA globular head domains by taking advantage of the conserved disulfide bond Cys52-Cys277 which demarcates the border between the head and stalk domains.

Thus, through substituting the parental head domain with the head domain of another HA, a panel of chimeric HAs with the same stalk but different globular heads was generated. The design was tested across multiple subtypes, including the PR8 stalk domain with Cal/09 and VN H5 globular heads. In addition, an H7 globular head was placed on an H3 stalk domain. These constructs cover both phylogenetic groups of the influenza HA protein. Each construct was expressed on the cell surface and retained fusion activity. The generation of recombinant viruses bearing the chimeric HAs further validated that the HAs fold correctly and retain biological functions.

## 6.6 EXAMPLE 6: CHIMERIC HEMAGGLUTININ CONSTRUCTS AS A UNIVERSAL INFLUENZA VACCINE

**[00537]** This example demonstrates the protective efficacy of a stalk-specific immune response that can be elicited through vaccination with chimeric hemagglutinin (cHA) constructs, proteins that contain unique hemagglutinin head and stalk combinations.

### 6.6.1 Materials and Methods

#### 6.6.1.1 Cells and viruses

**[00538]** 293T and MDCK cells were obtained from ATCC and were maintained in Dulbeccos's Modified Eagle's medium (DMEM) and Minimal Essential Medium (both from Gibco). Each were supplemented with 10% fetal calf serum (HyClone), and 100 units/ml of penicillin-100 μg/ml of streptomycin (Pen/Strep, Gibco).

**[00539]** Influenza virus A/Fort Monmouth/1/1947 (FM1) and A/Netherlands/602/2009 were passaged in mouse lungs and then grown in 10 day old embryonated chicken eggs for 48 hours. Low pathogenicity A/Vietnam/1203/04 (VN04):PR8 2:6 reassortant virus with the polybasic cleavage site removed (see, e.g., Steel et al., 2009, J Virol 83:1742-1753) and B/Yamagata/16/1988 virus were grown in 10-day old embryonated eggs for 48 hours at 37°C or 72 hours at 33°C, respectively.

**[00540]** Recombinant influenza viruses were produced by reverse genetics system as described above and as previously described (see, e.g., Quinlivan et al., 2005, J Virol 79:8431-8439). cH9/1 N1 virus, a virus expressing the HA globular head domain of an H9 virus atop an H1 stalk (from PR8 virus), and cH5/1 (H5 head (VN04), H1 stalk) N1 viruses were rescued in a similar manner as previously described (see, e.g., Pica et al., 2012, PNAS USA 109:2573-2578).

In order to generate the YAM-HA virus, the extracellular domain of the B/Yamagata/16/1988 (WT YAM) HA was substituted with the corresponding domain of A/Puerto Rico/8/1934 virus HA (see, e.g., Hai et al., 2011, Journal of virology 85:6832-6843). The reverse genetic plasmids encoding the other 7 WT YAM viral segments were constructed in a previous study (see, e.g., Hai et al., 2008, J Virol 82:10580-10590). Following rescue, cHA-expressing recombinant viruses were propagated in 10 day old embryonated chicken eggs for 48 hours at 37°C. YAM-HA virus was grown in 8-day old embryonated chicken eggs for 72 hours at 33°C.

**[00541]** Recombinant and wild-type viruses were titered on MDCK cells (ATCC) in the presence of TPCK trypsin as described above. cH5/1 N1 virus was partially purified over a 30% sucrose cushion for use in ELISA assays. cH9/1 N1, cH5/1 N1 and FM1 viruses were purified via gradient centrifugation and inactivated with formaldehyde diluted (1:4000) in PBS to be used as positive control vaccines.

#### 6.6.1.2 Generation of cH6/1 and cH9/1 protein constructs

**[00542]** Soluble cH6/1 and cH9/1 proteins were generated using a baculovirus expression system as described above and as previously described (see, e.g., Pica et al., 2012, PNAS USA 109:2573-2578). Briefly, baculotransfer vectors were first generated followed by transfection of bacmids into Sf9 cells. Recombinant baculovirus were then used to infect High Five cells at an MOI of 10. Supernatants were harvested 96 h postinfection and then incubated with Ni-NTA resin (Qiagen) for 2 h at 4°C to purify His-tagged recombinant cHA proteins. The slurry was loaded onto columns, and following washes, was eluted in pH 8 elution buffer (50 mM Na2HCO3, 300 mM NaCl, 250 mM imidazole). Pooled fractions that contained protein were buffer-exchanged in PBS and concentrated using an Amicon Ultra centrifugal filter unit (Millipore) with a 10-kDa molecular mass cutoff in a swinging bucket rotor. Protein purity and identity were tested by SDS/PAGE, Coomassie staining, and Western blot. Final protein concentrations were determined with Bradford reagent.

#### 6.6.1.3 Animals

**[00543]** Animals were allowed access to food and water ad libitum and kept on a 12 hour light/dark cycle. Female 6-8 week old BALB/c mice (Jackson Laboratories) were anesthetized for all intranasal procedures with intraperitoneal (IP) injection of 0.1 ml of ketamine/xylazine (0.15 mg ketamine and 0.03 mg xylazine).

#### 6.6.1.4 Vaccination and challenge experiments

**[00544]** Naïve 6-8 week old female BALB/c mice were vaccinated with cH9/1 protein, intranasally (10ug) in the presence of adjuvant R848 (Invitrogen) and intraperitoneally (10ug) with Addavax, an MF59-like adjuvant (Invitrogen). Animals were boosted with cH6/1 protein, or BSA (BioRad) three weeks post prime. Booster vaccinations were also administered intranasally (10ug) and intraperitoneally (10ug), though with poly I:C as an adjuvant (Invitrogen). Inactivated FM1 virus (1ug) was administered intramuscularly in a volume of 50ul as a positive control. Three weeks post boost, animals were bled and sera was harvested, and animals were challenged with 5 LD50 of FM1 virus. Weights were monitored for 14 days post challenge.

**[00545]** In other experiments, animals were primed with cH9/1 encoding plasmid DNA (80 ug, TriGrid delivery system; Ichor Medical Systems) and then boosted three weeks later with cH6/1 or cH9/1 (control) protein administered with polyI:C intranasally (10 ug) and intramuscularly (10 ug). The boost was repeated three weeks later with cH5/1 or cH9/1 (control) protein. Control animals were DNA electroporated with cH9/1 coding DNA as well but were boosted twice with BSA (in a similar way as the treatment group). Positive control animals received either inactivated FM1 or PR8 virus (1 μg) or 1 μg of pH1N1 monovalent split vaccine intramuscularly (BEI). Animals were then challenged 3-5 weeks post boost with 5 LD50 of PR8 or FM1 or 10 LD50 of pH1N1 virus. Animals used for CD8+ T-cell depletion were treated 48 and 24 hours prior to challenge with 300 μg of a anti-CD8+ T-cell antibody (see, e.g., M.L. Salem, 2000, Int. J. Immunopharmacol. 22:707) (from hybridoma line 2.43, purchased from ATCC) and challenged with 5 LD50 of PR8 virus. Weights were monitored for 14 days post challenge. A 20% cutoff was used for all viruses.

**[00546]** For other experiments, mice were inoculated with YAM-HA or WT YAM virus, and then vaccinated with BSA or cH6/1 protein in the presence of poly I:C intramuscularly and intraperitoneally three weeks later. Naïve animals served as an additional control. All animals were bled and challenged 3-5 weeks following vaccination with 250 LD50 cH9/1 N1 virus, or 10LD50 of 2:6 reassortant H5 virus with the polybasic cleavage site removed in the PR8 background (see, e.g., Steel et al., 2009, J Virol 83:1742-1753). Formaldehyde-inactivated cH9/1 N1 virus (1ug) and cH5/1 N1 virus were administered intramuscularly in a volume of 50ul as a positive control for the appropriate viral challenge. Animals were euthanized if they lost

more than 30% of their initial body weight following challenge, according to institutional guidelines. A 20% cutoff was used for infection with the less pathogenic cH9/1 N1 and A/Netherlands/602/2009 viruses. For challenges using these two viruses, more stringent doses were used in order to appreciate death or substantial weight losses of all controls (250 or 10 LD50).

#### 6.6.1.5 Enzyme linked immunosorbant assay

**[00547]** Immulon 4HBX (Thermo Scientific) plates were coated overnight with partially purified cH5/1 N1 virus diluted to 5ug/mL in PBS. Plates were blocked for 1 hour with 0.1 % Tween 20-PBS (TPBS) containing 3% non-fat milk powder, and then incubated with mouse sera serially diluted in TPBS containing 1% milk powder for 1 hour at room temperature. After three washes, plates were incubated for 1 hour at room temperature with alkaline phosphate (AP) linked anti-mouse IgG (γ-chain specific, Invitrogen). Plates were then washed three times with TPBS, developed with p-nitrophenylphosphate (PNPP) substrate (Zymed), stopped with 0.5M NaOH, and read at the optical density of 405nm. For all experiments, a Synergy 4 (BioTek) plate reader was used.

**[00548]** Stalk-specific antibody titers were detected by ELISA as described above. PR8 antigens were used to coat ELISA plates in order to quantify stalk-specific reactivity. To detect the neutralization capability of stalk-specific antibodies in vaccinated mice, sera were pooled and total serum IgG was purified.

**[00549]** Pseudoparticles expressing H5 HA were used in a pseudoparticle entry assay as previously described (see, e.g., Hai et al., 2012, J. Virol. 86:5774-5781 and N. Pica et al., 2012, PNAS 109:2573-2578). Upon entry, pseudoparticles express a luciferase reporter. Inhibition of this entry by IgG was quantified as the percentage of expression compared to non-IgG treated controls. Because animals had not been exposed to H5 globular head domains, these assays determined the degree to which stalk-specific antibodies produced by vaccination neutralize virus. Monoclonal antibody CR6261 and purified IgG from influenza B wild type infected mice were used as controls.

#### 6.6.1.6 Plaque reduction neutralization assay (PRNA)

**[00550]** Dilutions of mAbs were first pre-incubated with 60 to 80 plaque-forming units (pfu) of virus (cH9N1 influenza A virus) for 1 hour at RT on a shaker. The virus and purified IgG

mixture was then used to infect a monolayer of MDCK cells in duplicate in a 12-well format and incubated at 37°C for 1 hour with intermittent rocking every 10 minutes. The agar overlay was supplemented with corresponding IgG dilutions. At two days post infection (dpi), the monolayer was fixed with 4% PFA/1X PBS for 30 minutes. Cells were blocked with 5% NF-milk/1X PBS for 30 minutes at RT and were incubated accordingly with either with an H9 specific monoclonal antibody (5 μg/mL) for 1 hour at RT. An anti-mouse secondary conjugated to HRP was used as a secondary at a 1:1000 dilution. Plaques were visualized using TrueBlue peroxidase substrate (KPL Inc.) and the reaction was stopped with tap water. Plaques were counted for each antibody and percent inhibition calculated over the no mAb group.

#### 6.6.1.7 Statistical tests

**[00551]** Statistical analyses were performed using a one tailed student's T test (Prism4, GraphPad). For Fig. 29C, all values are plotted as averages with standard error of the mean. Differences in survival were calculated with Kaplan Meier survival analysis with log rank significance test.

**[00552]** For analyses with P-values, P-values at or below 0.05 are considered statistically significant. Welch's correction was used if variances were determined to be statistically different. P-values at or below 0.05 are considered statistically significant. When comparing stalk serum reactivity to maximum weight loss in figure 29C, one value was detected as an outlier (modified Z-score > 3.5 standard deviations above the mean) according to the methods of Iglewicz and Hoaglin (see Iglewicz, B. a. H., D. 1993. Volume 16: How to detect and handle outliers. In E. Mykytka (ed.), The ASQC Basic References in Quality Control: Statistical Techniques. American Society of Quality Control), and was omitted from analyses.

### 6.6.2 Results

#### 6.6.2.1 Sequential vaccination with cHA constructs elicits HA stalk-specific antibodies and provides protection from lethal influenza challenge

**[00553]** It was hypothesized that constructs that express globular head domains from viruses with different antigenicities could stimulate polyclonal responses towards the stalk domain of the HA. To test this, mice were first vaccinated with cH9/1 soluble protein with adjuvant, whereby the stalk of the HA is from A/Puerto Rico/8/1934 (PR8) virus and the head from an H9 isolate. Three weeks post prime, mice were boosted with a second soluble cHA, cH6/1 (head from H6

virus, stalk from PR8 virus), with the intent of stimulating humoral responses towards the stalk domain of the molecule. (Mice vaccinated with inactivated FM1 virus served as a positive control). Three weeks post boost, mice were bled to assess serum reactivity to the H1 stalk domain, and then challenged with mouse-adapted A/Fort Mounmoth/1/1947 (FM1) virus. As shown in Figure 27A, vaccinated mice produced serum antibody responses towards the HA stalk domain. Following challenge with FM1, animals lost a considerable amount of weight (Figure 27B), though recovered after day 7 for an overall survival rate of 90% (Figure 27C). Even though mice had only been exposed to the globular head domains of H9 and H6 viruses, it was verified that all mice were HI negative to FM1 virus, and thereby confirmed that the protection elicited from vaccination was the result of an immune response specific to the stalk domain. Therefore, vaccination with PR8-based cHAs provides stalk-specific immunity that is protective in the face of an FM1 virus challenge.

#### 6.6.2.2 Vaccination with cH6/1 protein elicits stalk-specific immunity that mediates protection from cH9/1 N1 virus challenge

**[00554]** Although antibody responses were generated towards the stalk by administering two different soluble cHA constructs, a substantial degree of morbidity was seen following FM1 challenge. Because mice are immunologically naïve to influenza virus, it was possible that multiple exposures to influenza virus followed by the introduction of an antigenically distinct head was required in order to induce high serum antibody titers against the HA stalk. Enhanced stimulation of serum antibody titers with specificity to the hemagglutinin stalk may also require infection, and may explain why a robust protection following prime and boost with cHA proteins alone was not observed.

**[00555]** In order to stimulate immune responses towards the viral hemagglutinin, but not generate protective immunity to other viral proteins, a recombinant B/Yamagata/16/1988 virus was constructed that expresses the ectodomain of the HA from PR8 virus (YAM-HA) (see, e.g., Hai et al., 2011, Journal of virology 85:6832-6843). Mice were inoculated with YAM-HA in order to mimic prior exposures to influenza virus, and then vaccinated 3 weeks later with BSA or cH6/1 protein. As an additional control, mice were infected with wild-type B/Yamagata/16/1988 (WT YAM) virus and vaccinated with BSA. An influenza A virus that expressed the cH9/1 (H9 head, H1 stalk) was then used as the challenge virus, in order to definitively demonstrate the protective nature of an immune response directed only towards the HA stalk. Again, because

animals were exposed to the globular head domains from H1 and H6 viruses, the protection seen following challenge with a virus that expressed the cH9/1 HA was most likely a result of immunity towards the H1 stalk domain.

**[00556]** As shown in Figure 28A, animals that received cH6/1 protein vaccine following YAM-HA exposure were completely protected from 250 LD50 challenge with a cH9/1 expressing virus in the PR8 background. Animals vaccinated with cH6/1 soluble protein lost statistically less weight on days 3, 4, and 5 compared to animals that were vaccinated with BSA. This protection from weight loss resulted in increased survival in the group vaccinated with cH6/1, compared to the cohort vaccinated with BSA ($p = 0.038$; Figure 28B). Naïve animals and those inoculated with WT YAM were not protected from infection, demonstrating that any protection that was seen in the other vaccination groups was not a result of viral replication, but was instead a specific response to the H1 stalk domain. Because animals were exposed to the globular head domains from H1 and H6 viruses, and were HI negative to the cH9/1 challenge virus, it is believed that the protection seen here is a result of immunity towards the H1 stalk domain.

**[00557]** It is of note that monoclonal antibodies with specificities to the HA stalk have been isolated from individuals infected with or vaccinated against seasonal H1N1 viruses (see, e.g., Corti et al., 2010, The Journal of clinical investigation 120:1663-1673; Corti et al., 2011, Science 333:850-856; Ekiert et al., 2011, Science 333:843-850; Sui et al., 2009, Nat Struct Mol Biol 16:265-273; Throsby et al., 2008, PLoS One 3:e3942), and stalk titers have been appreciated in individuals not infected with the pH1N1 virus, although at lower levels (see, e.g., Pica et al., 2012, PNAS USA 109:2573-2578). As such, it is not surprising that YAM-HA inoculated animals were able to generate some degree of stalk titer. Vaccination with the cH6/1 construct, however, increased serum stalk titers by 4 fold (reciprocal dilutions that yielded equivalent OD values) (Fig. 28C, and protected animals from substantial weight loss and death (Fig. 28A and 28B). Vaccination with the cH6/1 construct elicited the production of stalk-specific IgG that neutralized virus with 100% efficiency (YAM-HA +BSA) (Figure 28D) whereas serum from prime only animals exhibited neutralizing levels barely above background (YAM-HA +BSA). Indeed, animals inoculated with YAM-HA and then vaccinated with BSA had statistically similar survival rates to those that were inoculated with WT YAM virus and vaccinated with BSA ($p = 0.058$). In contrast, the use of cH6/1 protein as a vaccine yielded 100% survival from

challenge, a rate that was highly significant when compared to that of animals inoculated with WT YAM ($p < .0001$). Survival was also enhanced when compared to that of mice inoculated with YAM-HA and vaccinated with BSA ($p = 0.038$). These differences were not reflected in the pseudoparticle entry assay, as IgG from YAM-HA + BSA mice and YAM-HA + cH6/1 mice inhibited the entry of pseudoparticles encoding an H5 HA with similar efficiency (Fig. 28E). It is important to note that the latter assay only detects the ability of antibodies to block entry of pseudoparticles. Therefore, the effects of stalk-antibodies downstream of entry and/or their interaction with infected (immune) cells would not be detected in this assay. This might explain why differences in neutralization were not observed between the two groups and did not reflect the *in vivo* findings. Nonetheless, the antibodies elicited by these infection protocols were stalk specific and were broadly neutralizing. Because the challenge virus only encodes the stalk domain from an H1 virus, it can be concluded that the protection seen was the result of the host immune response to the HA stalk domain that was stimulated through cH6/1 vaccination.

#### 6.6.2.3 Vaccination with cH6/1 protein protects mice from lethal H5 influenza virus challenge

**[00558]** Whether vaccination with cH6/1 protein could protect mice from challenge with an H5 virus was next ascertained. Mice were inoculated and vaccinated as described above, and challenged with 10 LD50 of a 2:6 reassortant virus that expresses the HA and NA from A/Vietnam/1203/2004 virus in the PR8 background (see, e.g., Steel et al., 2009, J Virol 83:1742-1753). As expected, naïve animals and those inoculated with WT YAM virus were not protected from challenge and succumbed to infection by day 8. Animals inoculated with YAM-HA virus and vaccinated with BSA were marginally protected from challenge, with a survival rate of 40%. Increased protection was seen when animals were vaccinated with cH6/1 protein, with 90% survival. The difference in survival rates between the two vaccine groups approached statistical significance ($p = 0.06$), although mice vaccinated with cH6/1 protein survived for a statically longer time ($p = 0.037$) (Figure 29A and 29B). When comparing reactivity to the HA stalk to the % maximal weight loss over the monitoring period following H5 challenge, an inverse correlation was detected, whereby animals with higher serum stalk titers tended to lose less weight following challenge (Figure 429C), supporting the notion that cH6/1 can boost HA-stalk based immunity.

**[00559]** Using challenge viruses with HA globular head domains to which vaccinated mice were immunologically naïve and HI negative, the results indicate that protection from challenge following vaccination was solely based on an immune response towards the HA stalk. To exclude the possibility that cross reactive antibodies towards the receptor binding site could be playing a role in the protection seen here, mice were all tested for HI and found to be HI negative to their respective challenge viruses.

#### 6.6.2.4 Vaccination with cHA elicits stalk-specific immunity that mediates protection from H1N1 virus challenges

**[00560]** Stalk-specific antibodies have been detected in human sera (see, e.g., Figs. 15A and 15B; M. Thorsby et al., 2008, PLoS One 3:e3942, D.C. Ekiert et al., 2009, Science 324:246-251, D.C. Ekiert et al., 2011, Science 333:843-850, J. Wrammert et al., 2011, J. Exp. Med. 208:181-193 and N. Pica et al., 2012, PNAS 109:2573-2578). Because it is possible that previous exposure to influenza virus HA is critical to the robust production of a stalk specific immune response, it was ascertained whether preexisting immunity to the influenza virus in mice could be recapitulated. It was hypothesized that this would more effectively protect against morbidity following virus challenge. To achieve this, mice were primed with a DNA expression vector (see, e.g., J. Steel et al, 2010, MBio 1(1), pii:e00018-10) that encodes cH9/1, then were boosted with soluble cH6/1 protein, followed by cH5/1 protein (H5 head, H1 stalk), and finally challenged with a panel of H1N1 viruses (Figs. 30A-30F). Following infection with FM1 (Figs. 30A and 30B), A/Netherlands/602/2009 (pH1N1) (Figs. 30C and 30D) and PR8 viruses (Figs. 30E and 30F), all cHA-vaccinated animals were protected from challenge and displayed only minimal amounts of weight loss, if any. In contrast, negative control animals that received BSA following priming with cH9/1 DNA lost considerable amounts of weight and, with the exception of one animal, succumbed to infection by day 9 (Figs. 30A-30F). The survival of the cHA-vaccinated animals in each of the challenge experiments was significantly different from that of controls (Figs. 30B, 30D and 30F). To confirm that the protection elicited was a result of stalk-specific humoral immunity, all mice were confirmed to be HI negative to each challenge virus though the sera were capable of binding H1 HA by ELISA (Fig. 30G), confirming the production of stalk specific antibodies by our vaccination protocol. Because it is possible that CD8 T cells directed towards epitopes within the HA stalk could be playing a role in the protection seen here (see, e.g., M. Tamura et al., J. Virol. 72:9404-9406), mice were vaccinated and depleted of CD8

T cells by administering monoclonal antibody 2.43 prior to PR8 challenge (M.L. Salem, 2000, Int. J. Immunopharmacol. 22:707-718). Depletion did not affect weight loss nor survival outcomes, implicating a humoral response in the protection elicited by vaccination (Figs. 30H and 30I). Therefore, an adaptive humoral immune response towards the HA stalk, and not the head, was providing protection against the three different H1N1 viruses.

**[00561]** In order to further validate that the cHA-based vaccination protocol induced stalk-specific antibodies with neutralizing capability against other subtypes, the ability of purified IgG from vaccinated mice to block the entry of pseudoparticles that harbor an H2 HA was tested. Because pseudoparticles express a luciferase reporter gene following entry, neutralizing activity was measured by the absence of luciferase enzymatic activity in cell supernatants (R. Hai et al., 2012, J. Virol. 86:5774-5781 and N. Pica et al., 2012, PNAS 109:2573-2578). Consistent with the protection seen following challenge, IgG purified from vaccinated mice inhibited the entry of pseudoparticles in a dose-dependent manner and with similar efficacy to that of CR6261, a monoclonal antibody with specificity to the HA stalk that was used as the positive control (Fig. 30J). The vaccination protocol, therefore, elicited stalk antibodies with broad specificities, capable of neutralizing other group 1 HAs like H2.

### 6.6.3 Conclusion

**[00562]** This example demonstrates the protective effect of a stalk-specific immune response that can be elicited through vaccination with chimeric HAs. It was demonstrated that an immune response directed towards the HA stalk was sufficient for protection from viral challenge, and that this vaccination protocol provided heterosubtypic protection. A similar strategy could be developed in humans to provide protection against a broad range of influenza viruses, negating the need for annual vaccination, and enhancing pandemic preparedness.

## 6.7 EXAMPLE 7: A CARBOXY-TERMINAL TRIMERIZATION DOMAIN STABILIZES CONFORMATIONAL EPITOPES ON THE STALK DOMAIN OF SOLUBLE RECOMBINANT HEMAGGLUTININ SUBSTRATES

**[00563]** This example demonstrates that a carboxy-terminal trimerization domain is important to the structural integrity of stalk epitopes on recombinant soluble influenza virus hemagglutinin.

### 6.7.1 Materials and Methods

#### 6.7.1.1 Cells

**[00564]** Sf9 insect cells (ATCC # CRL-1711) were grown in TMN-FH medium (Gemini Bio-Products) supplemented with 10% FBS (Atlanta Biologicals), 0.1% Pluronic F68 (Sigma) and a Penicillin-Streptomycin antibiotic (Gibco) mixture. BTI-TN-5B1-4 cells (High Five - Vienna Institute of Biotechnology subclone) were grown in HyClone SFX serum free medium (Fisher Scientific) supplemented with Penicillin-Streptomycin antibiotic mixture (Gibco).

#### 6.7.1.2 Cloning and recombinant baculovirus generation

**[00565]** Sequences coding for HAs of H1 strains A/Puerto Rico/8/34 (PR8), A/California/04/09 (Cal09), H2 strain A/Japan/305/57 (JAP57), H3 strains A/Hong Kong/1/68 (HK68), A/Wisconsin/67/05 (Wisc05) and H5 strain A/Viet Nam/1203/04 (VN04 - with removed polybasic cleavage site; see Steel et al., 2009, J Virol 83: 1742-1753) were amplified from pCAGGS plasmids by polymerase chain reaction and cloned into a modified pFastBac vector (Invitrogen) using BamHI or StuI and NotI restriction endonucleases (NEB). Two sets of constructs, HA without and with trimerization domain, were cloned: HA constructs without trimerization domain were designed so that the C-terminal transmembranee- and endodomain of the HA were replaced with a hexahistidine-tag (HA sequence ends with I509 for H1, V509 for H2 and H5 and G508 for H3; H3 numbering); the other set of constructs, HA with a trimerization domain, also lack the C-terminal transmembrane- and endodomains (HA sequence ends with V503 - H3 numbering) but include a thrombin cleavage site and a T4 foldon trimerization domain (see, e.g., Meier et al., 2004, J Mol Biol 344: 1051-1069) in addition to the C-terminal hexahistidine-tag (Figure 31). Generated recombinant pFastBac clones were transformed into DH10Bac bacteria (Invitrogen) according to the manufacturer's instructions and recombinant bacmids were prepared with a PureLink Plasmid Filter Midiprep kit (Invitrogen). Recombinant bacmids were transformed into Sf9 cells using Cellfectin II (Invitrogen) for rescue of recombinant baculovirus. All sequences were confirmed by Sanger sequencing.

#### 6.7.1.3 Protein expression, purification and characterization

**[00566]** Baculovirus was amplified in Sf9 cells to a passage 3 stock and then used to infect BTI-TN-5B1-4 (High Five) cells at $1x10^6$ cells/ml in HyClone SFX serum free media (Fisher Scientific) at a multiplicity of infection of 10. Expression was carried out in 1000 ml shaker flasks for 96 hours at 28°C. After 96 hours, supernatants were cleared by low speed

centrifugation (5000g, 4°C, 20 min) and incubated with Ni-NTA (Qiagen) resin (3ml slurry for 250 ml of culture supernatant) for two hours at room temperature (RT). The resin-supernatant mixture was then passed over 10 ml polypropylene columns (Qiagen). The retained resin was washed four times with 15 ml of washing buffer (50 mM $Na_2HCO_3$, 300 mM NaCl, 20 mM imidazole, pH 8) and protein was eluted with elution buffer (50 mM $Na_2HCO_3$, 300 mM NaCl, 300 mM imidazole, pH 8). The eluate was concentrated using Amicon Ultracell (Millipore) centrifugation units with a cut-off of 30 kDa and buffer was changed to phosphate buffered saline (PBS) of pH 7.4. Protein concentration was quantified using Quickstart Bradford Dye Reagent (Bio-Rad) with a bovine serum albumin standard curve. Protein purity, integrity and identity was assessed by sodium dodecyl sulfate polyacrylamide gel electrophoresis (SDS-PAGE) (4-20% polyacrylamide - Mini PROTEAN TGX gels, Bio-Rad), Coomassie staining and Western blot or enzyme linked immunosorbent assay (ELISA). Extent of trimerization and/or multimerization was tested by crosslinking of HA with bis-[sulfosuccinimidyl]suberate ($BS^3$ - Fisher Scientific) according to the manufacturer's recommendations. Briefly, 3 μg of HA were incubated in 30 μl of PBS in the presence of a 25 fold molar excess of $BS^3$ crosslinker. The mixture was incubated at RT for 30 minutes and then $BS^3$ was quenched by adding 1M Tris-HCl buffer (pH 8) to a final concentration of 50 mM. Subsequently SDS-PAGE and/or Western blot analysis with a mouse anti-his primary antibody (Sigma) and anti-mouse horseradish peroxidase (Santa Cruz Biotechnology) or alkaline phosphatase (Santa Cruz Biotechnology) conjugated secondary antibody was performed.

#### 6.7.1.4 Enzyme linked immunosorbent assay

**[00567]** Immunolon 4HBX (Fisher Scientific) plates were coated with recombinant HA with and without trimerization domain at a concentration of 5 μg/ml in coating buffer (0.1 M Na2CO3/NaHCO3, pH 9.2, 50 μl/well) overnight at 4°C. The plates were then blocked for one hour at RT with PBS (pH 7.4) containing 1% Tween 20 (TBPS) and 3% non-fat dry milk powder. After blocking, plates were washed once with TPBS and then incubated with three fold dilutions of monoclonal antibody or sera (100 μl per well in TPBS with 1% milk powder – monoclonal antibody starting concentration 30 μg/ml; 1:100 dilution for sera) for one hour at RT. Plates were then washed trice with 100 μl of TPBS and incubated for another hour at RT with horse radish peroxidase conjugated anti-mouse IgG (Santa Cruz Biotechnology) or anti-human Fab secondary antibody (Sigma) at a dilution of 1:3000 (50 μl per well). After three more

washes, plates were developed using SigmaFAST OPD substrate (Sigma) (100 µl/well), stopped with 3M HCl (50 µl/well) and read at an absorption of 490 nm on a Synergy 4 (BioTek) plate reader. The obtained read-out was background subtracted with values from secondary antibody-only incubated wells.

**[00568]** For stability studies, HA from PR8 virus with trimerization domain was stored at 4°C for 60 days, or at -80°C and went through one (standard), two, three or four freeze-thaw cycles. Stability of head versus stalk binding antibodies was compared using PY102 and C179 monoclonal antibodies. Antibody-HA combinations in ELISA were done in triplicates except for stability studies where duplicates were used.

### 6.7.2 Results

#### 6.7.2.1 A C-terminal trimerization domain stabilizes HAs and induces trimer formation

**[00569]** The extracellular domain of various group 1 and group 2 HAs were expressed in soluble form with or without a C-terminal T4 phage trimerization domain (Figure 31) in the baculoviral expression system. Proteins were harvested 96 hours post infection and purified via a C-terminal hexahistidine-tag using a Ni-NTA column. Purified protein was concentrated using ultrafiltration spin columns, assessed for protein integrity and impurities by SDS-PAGE and Coomassie staining and quantified with Bradford reagent. Based on the amino acid sequence and the fact that baculovirus expressed full length HAs without polybasic cleavage site are usually uncleaved, the extracellular domain of HA would have an expected molecular mass of approximately 60 kDa per monomer (or 180 kDa per trimer) without taking glycosylation into account. Cal09 (H1), JAP57 (H2) and VN04 (H5 without polybasic cleavage site) HA without trimerization domain seemed to be partially cleaved into HA1 and HA2 as indicated by the presence of bands at approximately 40 kDa (HA1) and 25 kDa (HA2) in addition to the uncleaved HA band at 60 kDa (HA0). Based on the exclusive presence of a 60 kDa band for Cal09, JAP57 and VN04 HAs with trimerization domains in the non-reducing, denaturing SDS-PAGE, it can be assumed that these proteins are expressed mostly as an uncleaved HA0 (Figure 32A). Additionally, preparations of Wisc05 (H3) HA without a trimerization domain showed a degradation product at 40 kDa that was reactive when probed with an anti-stalk antibody (12D1). This species was thus likely a product of non-specific cleavage. Wisc05 HA with trimerization

domain appeared only as an HA0 band (Figure 32A). PR8 and HK68 HA appeared to be very stable (present as HA0) even in the absence of a trimerization domain.

**[00570]** HAs were crosslinked with and without T4 trimerization domain using BS3, a hydrophilic 11 Ångstrom chemical crosslinker that was recently used to show trimerization for HAs (see, e.g., Weldon et al., 2010, PLoS One 5). After crosslinking, samples were diluted in a reducing, denaturing loading dye and resolved on a reducing, denaturing SDS-PAGE gel. Group 1 HAs without trimerization domain formed high molecular weight oligomers that barely ran into the running gel and were mostly retained in the stacking gel (Figure 32B and 32C). The strongest phenotype was detected for VN04 and JAP57; other group 1 HAs also formed additional trimers (approximately 230 kDa), dimers (130 to 150 kDa) and monomers (60 kDa) (Figure 32B and 32C). Group 1 HAs with trimerization domain formed mostly trimers that ran at approximately 230 kD on the SDS-PAGE gel and formed a defined band in the running gel. However, they also formed dimers (approximately 130 to 150 kDa, strongest for Cal09) and monomers (60 kDa). Group 2 HAs behaved differently: HK68 HA formed predominantly trimers and to some degree dimers regardless of the presence of a trimerization domain. Wisc05 HA showed mainly dimerization in the absence of a trimerization domain, while HA with the T4 domain was mostly trimerized.

#### 6.7.2.2 A C-terminal trimerization domain strongly enhances binding of stalk-reactive antibodies to HA substrates

**[00571]** The reactivity of a panel of broadly reactive, neutralizing antibodies to the HA constructs was assessed in order to determine differential binding of these antibodies to HA substrates with and without trimerization domain. Stalk-specific antibodies mAb C179, mouse mAb 6F12, human mAb CR6261 (all group 1 specific); and mouse mAb 12D1 and human mAb CR8020 (both group 2 specific) were used in the experiment. Four other stalk-reactive antibodies, KB2, BD3, GG3 and IB11, that were recently isolated and characterized to have reactivity to both H1 and H5 Has also were used in the experiment. As a control, strain specific antibodies that are known to bind to the globular head domain of HA were used. As additional controls, sera of mice sub-lethally infected with influenza virus strains (PR8, Cal09, H3, VN04) or vaccinated with VLPs (JAP57) was used. Antibodies C179, CR6261 and 6F12 showed a strong binding phenotype to both H1 HAs that were tested (Cal09 and PR8). It is of note that they bound exclusively to HAs that had a trimerization domain (Figure 33A and 33B); no

binding was observed to HAs without a trimerization domain. Similar binding characteristics were seen with the four other stalk-reactive broadly neutralizing H1-H5 antibodies. In contrast, head-specific antibodies, such as 7B2 (Cal09) and PY102 (PR8), reacted with HAs irrespective of the expression of a trimerization domain and these findings were confirmed using sera from Cal09 or PR8 infected animals (Figure 33A and 33B).

**[00572]** This effect is not specific to the H1 subtype - when testing the binding of C179 and CR6261 to JAP57 (H2) and VN04 (H5) HAs with and without a trimerization domain, a similar phenotype was observed, where these antibodies only reacted with trimerized forms of the protein (Figure 34A and 34B). The same result was seen when reactivity of the four H1-H5 antibodies was assessed. Head-specific antibodies 8F8 (JAP57) and mAb#8 (VN04) or polyclonal anti-H2 or anti-H5 sera recognized both forms of HA equally well.

**[00573]** For group 2 HA-binding antibodies a different pattern emerged. In order to test the effects of a trimerization domain on reactivity of stalk antibodies with group 2 HAs, broadly reactive antibodies CR8020 and 12D1 were used. CR8020 binds a conformational epitope in group 2 HAs, while 12D1 is thought to bind to a linear epitope within the long alpha helix (LAH) of the HA2 subunit. CR8020 binding to HK68 and Wisc05 HAs with trimerization domains was greatly enhanced over binding to HAs without trimerization domain (Figure 35A and 35B). However, lack of the trimerization domain did not completely abolish binding as seen with group 1 HAs. 12D1 did not distinguish between HAs with or without the trimerization domain (Figure 35).

### 6.7.3 Conclusion

**[00574]** The T4 trimerization domain allows for successful trimerization of soluble HA molecules and greatly increases the stability of these molecules following baculovirus expression.

## 6.8 EXAMPLE 8: INFLUENZA VIRUS EXPRESSING A CHIMERIC HA COMPRISING THE STEM DOMAIN OF AN H1 INFLUENZA VIRUS AND THE GLOBULAR HEAD DOMAIN OF AN H5 INFLUNZA VIRUS (CH5/1)

**[00575]** This example demonstrates that the engineering and rescue of an influenza virus expressing a chimeric HA comprising the stem domain of an H1 influenza virus and the globular

head domain of an H5 influnza virus (i.e, an influenza virus comprising a genome engineered to express a cH5/1 chimeric influenza hemagglutinin polypeptide).

**[00576]** A plasmid for rescue of influenza virus expressing a cH5/1 chimeric influenza hemagglutinin polypeptide was constructed by substituting codons for the globular head domain (53 to 276, H3 numbering) in a rescue plasmid that carries the HA gene of A/California/04/09 with the globular head domain of A/Vietnam/1203/04 (H5). The sequence of the construct was confirmed by Sanger sequencing and expression in 293T cells was tested using Western blot analysis in accordance with the methods described above.

**[00577]** Generation of recombinant virus for rescue was accomplished using the approaches described in Example 5, above. The plasmid encoding the $cH5/1_{Cal09}$ HA was co-transfected into 293T cells with 7 complementary rescue plasmids that encode for the 7 other genomic segments of the influenza A virus (PR8 backbone). Supernatants were harvested on day one post transfection and were directly inoculated into 10 day old embryonated eggs. 48 hours post-inoculation eggs were chilled to 4°C and allantoic fluid was harvested. Virus growth was assessed by hemagglutination assay. Supernatants from positive eggs were plaqued on MDCK cells and single plaques were picked and propagated again in embryonated eggs. RNA from plaque purified viruses was isolated, reverse-transcribed and the sequence was confirmed by Sanger sequencing. The identity of the virus clones was proven by staining with a strictly H1 stalk-reactive antibody (6F12) and a strain specific anti-head antibody against A/Vietnam/1203/04 (H5), confirming the generation of and isolation of influenza virus comprising a genome engineered to express a cH5/1 chimeric influenza hemagglutinin polypeptide comprising the HA gene of A/California/04/09 and the globular head domain of A/Vietnam/1203/04 (H5).

## 6.9 EXAMPLE 9 HEMAGGLUTININ STALK-BASED UNIVERSAL VACCINE CONSTRUCTS PROTECT AGAINST GROUP 2 INFLUENZA A VIRUSES

**[00578]** This example demonstrates that a vaccination strategy involving the administration of a chimeric HA polypeptide comprising the stalk domain of an H3 hemagglutinin (group 2) induces in subjects broadly neutralizing anti-stalk antibodies that are highly cross-reactive to heterologous H3, H10, H14, H15 and H7 (derived from a novel Chinese H7N9 virus)

hemagglutinins. This example also demonstrates that these anti-stalk antibodies confer broad protection against influenza viruses expressing various group 3 hemagglutinins, including an H7 subtype.

### 6.9.1 Materials and Methods

**[00579]** **Cells and viruses.** Madin-Darby canine kidney (MDCK; ATCC CCL-34) and human embryonic kidney 293T (ATCC CRL-11268) cells were purchased from the American Type Culture Collection and were grown in Dulbecco's modified Eagle's medium (DMEM) (Gibco) and minimal essential medium (Gibco), respectively. Both media were supplemented with 10% fetal bovine serum (FBS; HyClone) and 100 units/ml of penicillin and 100 μg/ml of streptomycin (Pen-Strep; Gibco).

**[00580]** Chimeric and recombinant influenza viruses were produced by plasmid-based reverse genetics as described before (Margine *et al.,* 2013, *J. Virol.* 87:4728-4737; Hai *et al.*, 2012. *J. Virol.* 86:5774 –5781; Krammer *et al.*, 2013. *J. Virol.* 87:6542–6550). Virus strains A/Victoria/361/11 (H3N2; Vic11), A/Perth/16/09 (H3N2; Perth09), A/Philippines/2/82 (H3N2; Phil82), X-31 (H3N2; 6:2 reassortant of A/Puerto Rico/8/34 with HA and NA from A/Hong Kong/1/68), A/rhea/ North Carolina/39482/93 (H7N1; RheaH7), A/cH5/3N1 (expressing the H5 globular head domain of A/Viet Nam/1203/04, the H3 stalk domain from Perth09, and the NA and internal genes from A/Puerto Rico/8/34), A/Wyoming/03/03 (H3N2; WyoH3), A/Northern shoveler/Alaska/7MP1708/07 (H3N8), A/mallard/Interior Alaska/10BM01929/10 (H10N7), and B/cH7/3 (expressing the H7 globular head from A/mallard/Alberta/24/01 on top of the H3 stalk domain from A/Perth/16/09 in the B/Yamagata/16/88 background) were grown in 8- or 10-day-old embryonated chicken eggs for 48 h at 37°C (for influenza A viruses) or for 72 h at 33°C (for influenza B viruses) (Hai *et al.*, 2012. *J. Virol.* 86:5774 –5781; Hai *et al.*, 2011. *J. Virol.* 85:6832– 6843). A/Indiana/10/11 (H3N2 variant, H3N2v) was grown on MDCK cells. Virus titers were determined on MDCK cells in the presence of tosyl phenylalanyl chloromethyl ketone (TPCK)-treated trypsin. Vic11, Perth09, Phil82, X-31, RheaH7, and A/cH5/3N1 viruses were purified via sucrose density ultracentrifugation for enzyme-linked immunosorbent assays (ELISAs). Purified preparations of strains used as positive controls (Phil82, X-31, RheaH7, and A/cH5/3N1) were inactivated by formalin treatment. All viruses were handled under biosafety level 2 conditions. Viruses expressing cH5/3 and cH7/3 proteins contained the original H3 cleavage sites that are associated with a low-pathogenicity phenotype and were rescued in the

A/Puerto Rico/8/34 background, which is usually considered safe for humans (Beare *et al.*, 1975. *Lancet* ii:729 –732). The H7N1 isolate utilized shows a low pathogenicity phenotype in avian species as well (Joseph *et al.,* 2007. *J. Virol.* 81:10558:10566). Sf9 cells (ATCC CRL-1711) were maintained in *Trichoplusia ni* medium-formulation Hink (TNM-FH) (Gemini Bio-products) supplemented with 10% FBS, 1% Pluronic F68 (Sigma), and Pen-Strep (Gibco). *BTI-TN-5B1-4* (High Five) cells (ATCC CRL-10859) were grown in HyClone SFX serum-free insect cell medium (Fisher Sci- entific) containing Pen-Strep (Gibco).

**[00581] Recombinant protein expression.** Recombinant baculoviruses for the expression of cH4/3 (H4 globular head domain from A/duck/ Czech/56 in combination with the H3 stalk domain from Perth09), cH5/3 (H5 globular head domain from A/Viet Nam/1203/04 in combination with the stalk domain from Perth09), cH7/3 (H7 globular head from A/mallard/Alberta/24/01 on top of the H3 stalk domain of Perth09), and Perth09 HA were generated as described elsewhere (Margine *et al.*, 2013. *J. Virol.* 87:4728–4737; Krammer *et al.,* 2012. *PLoS One.* 7:e43603. doi:10.1371/journal.pone.0043603) and were propagated in Sf9 cells. For expression, High Five cells were infected with recombinant baculoviruses at a multiplicity of infection of approximately 10, transferred into Fernbach flasks, and incubated at 28°C, with shaking. Culture supernatants were harvested 96 h postinfection by low-speed centrifugation (5,500 relative centrifugal force [RCF], 10 min, 4°C) and were then incubated with Ni-nitrilotriacetic acid (NTA) resin (Qiagen) for 3 h at room temperature (RT), with shaking at 75 rpm in a rotational shaker. The resin-supernatant mixture was then passed over 10 ml polypropylene columns (Qiagen), washed four times with washing buffer (50 mM Na2HCO3, 300 mM NaCl, 20 mM imidazole, pH 8), and eluted with elution buffer (50 mM Na2HCO3, 300 mM NaCl, 250 mM imidazole, pH8). The eluted fractions were concentrated, and the buffer was exchanged against phosphate-buffered saline (PBS; pH 7.4) using Amicon Ultra centrifugal filter units (Millipore; 30-kDa molecular mass cutoff). Purity, identity, and integrity of the purified proteins were assessed by SDS-PAGE and Western blotting or ELISA, and protein concentration was measured using Bradford reagent (Bio-Rad). Soluble A/Perth/16/09 H3, A/Shang- hai/1/13 H7, and A/PR/8/34 H1 HAs for ELISAs were expressed in a similar way but as a fusion protein with a GCN4pII trimerization motif and a C-terminal Strep-Tag II via StrepTactin resin (GE Healthcare) to avoid background signal when used in ELISAs to assess stalk-reactive antibodies induced by the vaccine constructs (Krammer *et al.,* 2013. *J. Virol.* 87:6542– 6550).

**[00582]** **Animals, vaccination, and challenge.** All animal experiments were performed with 6- to 8-week-old female BALB/c mice (Jackson Laboratories) and in full compliance with the guidelines of the Icahn Sinai School of Medicine at Mount Sinai Institutional Animal Care and Use Committee. Animals had free access to food and water and were kept on a 12-h light-dark cycle. Animals were anesthetized for all intranasal procedures by administering 0.1 ml of a ketamine-xylazine mixture (0.15 mg/kg and 0.03 mg/kg) intraperitoneally.

**[00583]** For the initial experiment, naive 6- to 8-week-old BALB/c mice were vaccinated in the left calf muscle with DNA encoding a cH4/3 HA (Margine *et al.,* 2013. *J. Virol.* 87:4728–4737; Krammer *et al.,* 2013. *J. Virol.* 87:6542–6550; Steel *et al.,* 2010. *mBio* 1(1):e00018–10. doi:10.1128/mBio.00018-10), by in vivo electroporation using a TriGrid delivery system (Ichor Medical Systems). Three weeks later, animals were boosted intramuscularly (i.m.) and intranasally (i.n.) with 5 μg protein adjuvanted with 5 μg poly(I•C) (Invivogen) at each site (n = 9 or 10 animals per group). Prime-only animals (n = 5 per group) received the same amount of irrelevant protein (bovine serum albumin [BSA]), with the same amount of adjuvant, both i.m. and i.n. A second boost was administered 3 weeks later in the same manner but with cH7/3 protein. For the subset of mice dedicated to the H7N1 challenge, the cH7/3 protein was replaced by full-length Perth09 H3 protein. Prime-only animals received the corresponding BSA vaccination again. Positive-control animals (n = 5 per group) were vaccinated with 1 fl.g of inactivated matched challenge virus i.m., 3 weeks before challenge. Naive mice (n = 5 per group) were included as additional negative-control groups. Four weeks after the last boost, animals were anesthetized and infected with 5 50% lethal doses ($LD_{50}$) of Phil82, X-31, or RheaH7 viruses. Weight was monitored daily for a period of 14 days, and animals that lost 25% or more of their initial body weight were scored dead and humanely euthanized. Serum samples were collected preprime and prechallenge by submandibular bleeding.

**[00584]** For the second set of experiments, naive 6- to 8-week-old BALB/c mice were infected intranasally with a sublethal dose ($10^6$ PFU) of a recombinant influenza B virus vector (based on B/Yamagata/16/88) expressing the cH7/3 HA protein. Control animals received the same dose of wild-type (wt) influenza B virus (Bwt). The mice in the vaccine group were then boosted with cH5/3 protein (5 μg i.n. plus 5 μg i.m., each adjuvanted with 5 μg of poly(I•C), with the exception of a subset of animals dedicated to the cH5/3N1 virus challenge; these animals received recombinant Perth09 full-length H3 HA in the same manner instead of the

cH5/3 protein (n = 10 per group). Prime-only and vector control animals (n = 5 per group) received a boost with irrelevant protein instead (BSA; same amount, adjuvant, and administration routes as for the vaccine groups). Finally, animals received a second boost 3 weeks later with cH4/3 protein as described for the first boost. Again, prime-only and vector control animals received irrelevant protein, in the same manner. Naive mice (n = 5 per group) were included as additional negative-control groups. Positive-control animals (n = 5 per group) were vaccinated with 1 μg of inactivated matched challenge virus i.m., 3 weeks before virus challenge. Four weeks after the last boost, animals were anesthetized and challenged with 10 $LD_{50}$ of either Phil82 or X-31 or with 100 $LD_{50}$ of cH5/3N1 virus. Weight loss was monitored daily for a period of 14 days, and animals that lost 25% or more of their initial body weight were scored dead and humanely euthanized. Serum samples were collected preprime and prechallenge by submandibular bleeding. For lung titration experiments, mice were vaccinated as described above (cHA and Bwt-BSA-BSA groups, n = 3 mice per group) and were then infected with 5 X $10^4$ PFU of H3N2v or 1 X $10^5$ PFU of H3N8, WyoH3, or H10N7 virus. Lungs were harvested on day 3 postinfection and homogenized, and the 50% tissue culture infectious dose ($TCID_{50}$) was measured as described before (Miller *et al.*, 2013. *J. Infect. Dis.* 207:98 – 105).

**[00585]** For passive transfer experiments, sera from the latter set of experiments were collected from the (influenza B-vectored) vaccine group, positive-control group, vector control group, and naive animals. Sera from each group were then transferred by intraperitoneal injection into naive mice (6 to 8 weeks old, n = 5 per group, 300 μl serum per mouse), and mice were challenged with 5 $LD_{50}$ of Phil82 virus 2 h after the transfer. Weight was monitored daily for a period of 14 days, and animals that lost 30% or more of their initial body weight were scored dead and euthanized.

**[00586]** **ELISA.** ELISA plates (Immunolon 4 HBX) were either coated over-night at 4°C with purified virus (4 μg/ml) or purified protein (2 μg/ml) diluted in carbonate/bicarbonate coating buffer (pH 9.4). Plates were blocked for 1h at RT with PBS containing 0.1% Tween 20 (TPBS) and 3% nonfat dry-milk powder. Mouse serum was prediluted 1:100, serially diluted in 1:2 steps in TPBS containing 1% nonfat dry-milk powder, and incubated on the plates for 1h at RT. After extensive washing with TPBS (3X 100 μl/well), the plates were incubated for 1h at RT with an anti-mouse IgG horseradish peroxidase (HRP)-conjugated IgG (Santa Cruz) diluted

in TPBS containing 1% nonfat dry-milk powder. After three more washing steps with TPBS, plates were developed using the *o*-phenylenediamine dihydrochloride (SigmaFast OPD; Sigma) substrate. Reactions were stopped using 3 M HCl, and plates were read at an optical density at 490 nm.

**[00587]** Detection of IgA in nasal washes was performed with a similar assay except that an alkaline phosphatase (AP)-linked anti-mouse IgA antibody was used (Southern Biotech) diluted 1:500 and incubation steps at 37°C for 3h. Isotype distribution in serum was determined by ELISA using an isotyping kit (Invitrogen), which contains a collection of secondary antibodies specific for each subtype and an AP-conjugated tertiary antibody that allows for detection of binding.

**[00588]** **Pseudotyped particle neutralization assay.** The pseudotyped particle production protocol was adapted from previous studies (Hai *et al.,* 2012. *J. Virol.* 86:5774 –5781; Evans *et al.,* 2007. *Nature*, 446:801– 805; Pica *et al.,* 2012. *Proc. Natl. Acad. Sci. U. S. A.* 109:2573–2578). Briefly, 293-T cells were cotransfected with four plasmids encoding a provirus containing a luciferase reporter gene, the HIV Gag-Pol, the Vic11 HA protein, and the neuraminidase from influenza B virus B/Yamagata/16/88. Culture supernatants were collected 48 h posttransfection and filtered through a 0.45-μm-pore-size filter unit to remove cellular debris. The purified pseudotyped particles were incubated with different concentrations of inactivated mouse sera before being added to MDCK cells. The transduction procedure was carried out for 6h, cells were then washed, and fresh medium was placed over cells. The transduction procedures were performed in the presence of 1 μg/ml Polybrene (Sigma, St. Louis, MO). Luciferase activity was read 48h after transduction. The stalk-reactive monoclonal antibody 12D1 (Wang *et al.,* 2010. *PLoS Pathog.* 6:e1000796.doi:10.1371/journal.ppat.1000796) was used as a positive control with a starting concentration of 123 μg/ml.

**[00589]** **Immunofluorescence staining.** MDCK cells were transfected with plasmids expressing HAs from A/Anhui/1/13 (H7N9), A/Shanghai/1/13 (H7N9), A/chicken/Jalisco/12283/12 (H7N3), A/mallard/Gurjev/263/82 (H14N5), and A/wedge tailed shearwater/Western Australia/2576/79 (H15N9). Cells were transfected with the respective plasmid. Sixteen hours posttransfection, cells were fixed with 0.5% paraformaldehyde and stained with 1:200 dilution of sera collected from vaccinated animals (cH4/3DNA-cH5/3-H3) or were naive. Stalk-reactive antibodies FI6 (Corti *et al.,* 2011. *Science,* 333:850 – 856) and FBE9

(both used at a concentration of 10 μg/ml) served as positive controls, while serum collected from naive animals was used as a negative control. Secondary antibodies conjugated to Alexa 488 were used to visualize reactivity to the proteins. Images were taken on an LSM 510 Meta confocal microscope (Carl Zeiss MicroImaging GmbH, Jena, Germany) at a magnification of X10.**Statistical tests, hemagglutinin modeling, and phylogenetic analysis.** Statistical analyses were performed using Prism4 (GraphPad). All values are plotted as averages with standard deviations of the means. Differences in survival were calculated by using Kaplan-Meier survival analysis with log rank significance test. *P* values at or below 0.05 are considered statistically significant. In order to generate models of the wild-type and chimeric hemagglutinins, structures from the Protein Data Bank (PDB) were modeled by using the PyMol software (Delano Scientific). For modeling of the cH4/3 construct, the HA of A/Hong Kong/1/68 (HK68) (PBD identifier [ID] 1MQN) was used, and the H4 head domain was indicated with a different color (there is no H4 structure available). The cH5/3 HA was modeled with the stalk from HK68 HA (PBD ID 1MQN) and the globular head of an H5 virus (PBD ID 2FK0); the cH7/3 was modeled with the HK68 stalk domain and a head domain from an avian H7 virus (PDB ID 4DJ6). The chimeric challenge viruses were modeled by using the stalk structure of HK68 (PBD ID 1MQN) and head of H5 HA (PBD ID 4DJ6). Phylogenetic analysis was performed using ClustalW (EMBL-EBI). The protein sequences were downloaded from GenBank, and multiple alignments were performed using the ClustalW algorithm in Mega version 5.1. Phylogenetic trees were constructed using the FigTree software and the neighbor-joining method.

### 6.9.2 Results

**[00590] Chimeric HA constructs provide broad protection from challenge with divergent H3N2 viruses.** To induce broad protection against group 2 HA-expressing influenza viruses in the mouse model, antibodies against the conserved HA stalk domain were specifically boosted. To this end, a collection of cHA molecules expressing H3 stalk domains combined with various head domains were constructed (Margine *et al.*, 2013. *J. Virol.* 87:4728 – 4737; Hai *et al.*, 2012. *J. Virol.* 86:5774 –5781). Mice were primed intramuscularly (i.m.) with plasmid DNA encoding a cH4/3 HA (expressing an H4 globular head domain and an H3 stalk domain) (Fig. 37A). Three weeks later, mice were boosted with soluble cH5/3 protein (H3 stalk domain combined with an H5 globular head domain) via both the i.m. and intranasal (i.n.) routes. Both routes were utilized to ensure induction of systemic and mucosal immunity since both responses are important for

efficient protection against influenza virus infection. A second boost with cH7/3 protein (H7 globular head on top of an H3 stalk) followed 3 weeks later (Fig. 37A). It was hypothesized that by repeatedly exposing the animals to antigens expressing a common, unfettered (soluble, non-membrane-bound) stalk domain, the immunogenicity of this region, which currently used vaccination strategies induce only a subdominant response, could be enhanced (Wrammert *et al.,* 2008. *Nature* 453:667– 671; Margine *et al.,* 2013. *J. Virol.* 87:4728 – 4737).

**[00591]** Control animals either received only the DNA prime (prime-only control) or a matched inactivated challenge virus (positive control) or were naïve. To test the ability of this vaccine to protect against morbidity and mortality associated with influenza, mice were infected with two different H3N2 viruses. It is of note that all cHA-vaccinated animals were HI negative against the respective challenge strains. Upon infection with A/Philippines/2/82 virus (Phil82), the vaccinated animals lost minimal amounts of weight compared to no weight loss in the positive control, did not develop clinical symptoms, and were fully protected against mortality (Fig. 37B and C). Naïve animals, however, lost weight rapidly and succumbed to infection by day 9 (naïve control). Prime-only controls also exhibited rapid weight loss, and only 20% of them survived the viral challenge. A similar outcome was observed upon challenge with X-31, a virus that expresses the glycoproteins of the Hong Kong 1968 H3N2 virus (Fig. 37D and E).

**[00592]** Previous data demonstrates that sublethal infection with influenza viruses is one way to induce stalk-reactive antibodies in mice and humans (Margine *et al.,* 2013. *J. Virol.* 87:4728 – 4737; Pica *et al.,* 2012. *Proc. Natl. Acad. Sci. U. S. A.* 109:2573–2578; Krammer *et al.,* 2012. *J. Virol.* 86:10302–10307). Since most human individuals are exposed to influenza viruses multiple times throughout their lifetime, they generally have baseline levels of stalk-reactive antibodies. In order to mimic this preexisting immunity in the mouse model, an influenza B virus expressing a cH7/3 HA instead of the wild-type influenza B virus HA was rescued. A sublethal dose of this virus was used to prime mice, which were then vaccinated at 3-week intervals with cH5/3 followed by cH4/3 protein, both i.m. and i.n. (Fig. 38A). When challenged with either Phil82 or X-31, the animals showed no clinical signs of disease and minimal weight loss comparable to that of positive-control animals that received inactivated matched challenge strains (Fig. 38C, D, F, and G). Control animals infected sublethally with wild-type influenza B virus and vaccinated in a similar manner with an irrelevant protein (BSA), as well as naive mice and prime-only controls, lost weight rapidly and succumbed to both infections. Next, the ability

of the stalk-directed immunity to protect against more recent H3N2 isolates was tested. Since contemporary H3N2 viruses are not pathogenic in the mouse model, a cH5/3N1 virus expressing the H3 stalk domain of the recent vaccine strain A/Perth/16/09 (Perth09) and an NA from A/PR/8/34 (H1N1) was used for this purpose (Hai *et al.*, 2012. *J. Virol.* 86:5774 –5781). To assess the protection conferred by the stalk-reactive antibodies (and to exclude H5-H5 head reactive antibodies), the vaccination regimen was altered for this subset of mice and full-length H3 was administered instead of the cH5/3 protein (Fig. 38A). When challenging with a high dose (100 mouse $LD_{50}$[$mLD_{50}$]) of the cH5/3N1 virus, robust protection from weight loss was observed, as well as complete protection from mortality of the vaccinated animals. This demonstrated the efficacy of the HA stalk-based vaccine approach against contemporary H3N2 isolates (Fig. 38B and E). To test additional divergent H3 strains that do not induce mortality in the mouse model, lung titration experiments were performed. Animals vaccinated as described above were infected with H3N2 variant virus (H3N2v) (CDC. July 2012. *MMWR Morb. Mortal. Wkly. Rep.* 61:561), an avian H3N8 isolate (H3N8), and the human H3N2 A/Wyoming/03/03 strain (WyoH3). Day 3 postinfection, lung titers of vaccinated animals were low (close to the limit of detection), whereas high virus titers were detected in lungs collected from control animals (Bwt-BSA-BSA) (Fig. 37F and G and data not shown). Taken together, these data clearly show that the stalk-based vaccination strategy can provide robust protection against heterologous and heterosubtypic viruses in the mouse model of influenza.

**[00593] Vaccination with chimeric HA constructs induces a broad systemic and mucosal stalk-directed humoral response.** ELISAs were employed in order to characterize the stalk-directed antibody response induced by this vaccination regimen. Since the animals were exposed only to vector-expressed or recombinant HA but not to any other influenza A proteins, purified virus was able to be used as the substrate to measure the anti-stalk responses. Sera from both vaccination regimens (influenza B virus vectored or DNA primed) were tested for their reactivity to the challenge strains Phil82 and X-31, as well as to the current H3N2 vaccine strain A/Victoria/361/11 (Vic11), an H3N8 strain and HA protein from Perth09. While sera collected from animals that were naive, or that were exposed only to the DNA prime, exhibited low background level binding, there was high reactivity against all five viral strains in sera collected from vaccinated mice (Fig. 39A to E). Similarly, high stalk-directed antibody titers were detected in the sera of animals primed with the cHA-expressing influenza B virus (Fig. 39F to

H). Vector control (wild-type influenza B virus) and naive animals again only showed background reactivity, while the prime-only group (c7/3 HA-expressing influenza B virus) had an intermediate binding phenotype. The intermediate titers in the latter group were thought to be the result of replicating virus (Margine *et al.,* 2013. *J. Virol.* 87:4728 – 4737; Krammer *et al.,* 2012. *J. Virol.* 86:10302–10307). Isotype distribution revealed that the profile of the antibody response induced by the vaccine is balanced, with the majority of IgG being of the IgG1, IgG2a, or IgG2b subclass (see Fig. 41C).

**[00594]** In addition to the serum IgG titers, levels of secretory IgA on the mucosal surfaces of vaccinated mice were assessed. This revealed high reactivity to Perth09 H3 HA in nasal washes collected from the group of mice that received the vaccine, whereas nasal washes from control animals did not react to the substrate (see Fig. 41B). Although mucosal anti-stalk IgA antibodies, and their ability to block viral infection, have not been yet formally characterized, it is hypothesized that they contribute to the observed protection.

**[00595]** Broadly reactive anti-globular head antibodies have recently been described in the literature (Ekiert *et al.,* 2012. *Nature* 489:526 –532; Lee *et al.,* 2012. *Proc. Natl. Acad. Sci. U.S.A.* 109:17040-17045; Krause *et al.,* 2012. *J. Virol.* 86:6334 – 6340). Though rare in nature, these antibodies tend to recognize conserved regions of the receptor-binding site and recognize divergent globular head domains without closely following phylogenetic relatedness. Binding to head domains of both group 1 and group 2 HAs (*e.g.*, H1-H3 binding) has been described by these antibodies. To assess whether the cHA-based vaccination induces such antibodies, an additional ELISA with full-length H1 HA as the substrate was performed (see Fig. 41A). Sera from cHA-vaccinated animals did not react with this substrate, suggesting that cHA vaccination does not induce detectible levels of broadly reactive anti-head antibodies.

**[00596]** **The induced broadly reactive antibodies potently neutralize virus, both *in vitro* and *in vivo*.** To further test the *in vitro* cross-neutralizing nature of the stalk antibodies induced by the vaccination regimen, an entry inhibition assay with Vic11 HA-pseudotyped particles was performed. Serum from vaccinated animals inhibited cell entry of the pseudoparticles in a dose-dependent manner (see Fig. 41D). In contrast, serum from influenza B virus vector- infected control animals and naive mice showed no inhibitory activity in this assay.

**[00597]** A passive transfer experiment was performed in order to show that the vaccine-induced protection observed *in vivo* was due, at least in part, to neutralizing antibodies in serum.

Sera from vaccinated, positive-control, influenza B virus vector- infected, or naive animals were transferred into naive mice, which were then challenged with the Phil82 virus. Mice that received sera from vaccinated or positive-control groups were completely protected from mortality, whereas none of the animals that received sera from either of the negative-control groups survived (see Fig. 41E). These results indicate that the stalk-directed humoral response is sufficient to protect mice from lethal challenge.

**[00598] Vaccination with chimeric HA constructs induces stalk- based heterosubtypic immunity.** Antibodies that cross-neutralize divergent group 2 HA influenza viruses have been described in the literature (Wang *et al.*, 2010. *PLoS Pathog.* 6:e1000796. doi:10.1371/journal.ppat.1000796; Ekiert *et al.*, 2011. *Science* 333:843– 850). To test protection against a heterosubtypic H7N1 virus and exclude any involvement of head-directed antibodies in the observed protection, the DNA-protein-protein vaccination regimen described above was used, although the cH7/3 HA protein was replaced with full-length H3 HA (Fig. 40A). Both vaccinated and positive-control animals challenged with the avian H7N1 A/rhea/North Carolina/39482/93 strain (RheaH7) experienced a similar initial weight loss of approximately 15% (Fig. 40B). This is probably due to the high numbers of PFU/mouse lethal dose needed for this experimental viral challenge. However, mice from both groups regained the weight quickly, and the vaccine group displayed a 90% survival rate. Naive and prime-only animals, however, experienced severe weight loss and showed no or low (20%) survival, respectively. The results of the latter experiment demonstrate the true heterosubtypic nature of the immunity afforded by an HA stalk-directed response (Fig. 40C). To further evaluate the level of broadly neutralizing antibodies present in the sera, ELISAs were performed with purified H7N1 challenge virus as well as with recombinant H7 protein from the novel Chinese H7N9 virus strain (Gao *et al.,* 2013. *N. Engl. J. Med.* 368:1888-1897). Detection of high antibody titers in sera collected from these animals to the H7 HAs underlines the cross-reactive nature of the response induced by the H3 stalk domain (Fig. 40D and E, Fig. 41). In addition, a challenge experiment with an H10N7 virus was performed, with lung titers as the assay readout. Day 3 lung titers for vaccinated animals were in the range of $10^3$ $TCID_{50}$/ml, whereas mock-vaccinated animals showed a 10- to 100-fold-higher titer (Fig. 40F). Efficient binding of sera from cHA-vaccinated animals to cells expressing Eurasian and North American lineage H7 HAs, as well as H14 and H15 HAs, further proves the cross-reactive nature of this immune response (Fig. 40G and 42).

### 6.9.3 Discussion

**[00599]** Although the anti-stalk antibodies can be found in humans who have been exposed to influenza viruses via either vaccination or infection (Margine *et al.,* 2013. *J. Virol.* 87:4728 – 4737; Sui *et al.,* 2011. *Clin. Infect. Dis.* 52:1003–1009; Corti *et al.,* 2010. *J. Clin. Invest.* 120:1663–1673), they do seem to be rare in nature, and *in vivo* levels of these antibodies are likely too low to afford protection. Consequently, vaccines able to boost the levels of these broadly neutralizing stalk reactive antibodies could lead to universal protection against circulating human influenza virus strains, as well as potential pandemic avian viruses like the emerging Chinese H7N9 strain (Gao *et al.,* 2013. *N. Engl. J. Med.* 368:1888-1897). Based on the conservation of the stalk domain of the HA, it is likely that such a universal vaccine has to include three components: a group 1, a group 2, and an influenza B stalk-based antigen.

**[00600]** Animals sequentially vaccinated with chimeric HA constructs expressing an H3 stalk domain and divergent globular heads developed high titers of cross-reactive antibodies against the stalk domain. These antibodies were not only protective against a panel of H3N2 strains and an H3N8 virus but also provided robust protection against a hetero-subtypic challenge with avian H7N1 and H10N7 isolates, demonstrating a breadth that spans both clades of the group 2 HA-expressing viruses. This breadth is important in light of growing concerns about the pandemic potential of H3N2 variant (H3N2v) viruses and H3N8 viruses isolated from New England harbor seals and other zoonotic H3 strains (Baz *et al*., 2013. *J. Virol.* 87:6901– 6910; CDC. July 2012. *MMWR Morb. Mortal. Wkly. Rep.* 61:561; Anthony *et al*., 2012. *mBio* 3(4):e00166 –12. doi: 10.1128/mBio.00166-12), as well as H4-, H7-, and H10-expressing viruses that infect humans occasionally (Runstadler *et al.,* 2013. *Infect. Genet. Evol.* 17:162–187; Kayali *et al.,* 2011. *PLoS One* 6:e26818. doi:10.1371/journal.pone.0026818; Arzey *et al.,* 2012. *Emerg. Infect. Dis.* 18:814 – 816; CDC. 2012. *MMWR Morb. Mortal. Wkly. Rep.* 61:726 –727; Fouchier *et al.*, 2004. *Proc. Natl. Acad. Sci. U. S. A.* 101:1356 –1361; Tweed *et al.,* 2004. *Emerg. Infect. Dis.* 10:2196 – 2199). Importantly, this vaccination strategy also induced high titers of stalk-reactive antibodies against the H7 HA from the emerging Chinese H7N9 virus (Gao *et al.,* 2013. *N. Engl. J. Med.* 368:1888-1897). .

**[00601]** Humans are exposed to influenza viruses multiple times throughout their lifetime and therefore are likely to have preexisting memory B cells with specificities in the stalk domain. In an attempt to mimic this situation in the mouse model and to efficiently boost preexisting titers

of stalk-reactive antibodies, mice were preexposed to the H3 stalk domain by being sublethally infected with a recombinant influenza B virus expressing the H3 stalk domain in combination with an irrelevant globular head domain. Upon subsequent vaccination with cHA constructs containing the same stalk domain but different heads, the levels of stalk-reactive antibodies were efficiently boosted and protected mice from challenge with a panel of H3N2 influenza virus strains spanning from 1968 to 2009. Serum from vaccinated mice showed good reactivity to a wide range of H3N2 virus substrates as well as an H7N1 virus and an H7N9 HA protein substrate. Vaccinated animals also showed reduced lung titers after infection with H3N2v, H3N8, and H10N7 infection. Furthermore, the serum showed neutralizing activity and could protect mice in a passive transfer challenge experiment. These findings shed light on the mechanism of neutralization elicited by this vaccination strategy and suggest that an antibody-mediated mechanism, likely based on virus neutralization, is mediating protection. A contribution by CD8+ and CD4+ T cells to protection cannot be ruled out at this point, although transfer of serum alone was sufficient to protect from challenge. Enhanced pathogenicity induced by nonneutralizing cross-reactive anti-influenza antibodies has been proposed as a possible reason for the high pathogenicity of the novel Chinese H7N9 virus in the elderly (Skowronski *et al.*, 2013. *Euro Surveill.* 18:pii=20465. http://www.eurosurveillance.org/View Article.aspx? ArticleId=20465). Enhanced pathogenicity in cHA-vaccinated animals that had high titers of cross-neutralizing antibodies was not observed. In fact, the animals were protected from morbidity and mortality and the virus was cleared faster.

**[00602]** The present experiments were designed to show that protection against group 2 HA-expressing viruses can be mediated by stalk-reactive antibodies alone. As described herein, a human vaccine strategy might be based on either inactivated or attenuated viruses that express cHA structures in combination with a functional neuraminidase and all internal proteins of the influenza virus. Replacement of the globular head domain of H3 HA, to which humans have memory responses, by an "exotic" irrelevant head domain to which humans are naive would, in addition to boosting stalk-reactive antibodies (Krammer *et al.,* 2013. *J. Virol.* 87:6542– 6550; Miller *et al.*, 2013. J. *Infect. Dis.* 207:98 –105; Pica *et al.,* 2012. *Proc. Natl. Acad. Sci. U. S. A.* 109:2573–2578; Li *et al.,* 2012. *Proc. Natl. Acad. Sci. U.S.A.* 109:9047–9052; Wrammert *et al.,* 2011. *J. Exp. Med.* 208:181–193; Thomson *et al.,* 2012. *Front. Immunol.* 3:87), should enhance levels of antibodies directed against the NA. Furthermore, the presence of internal proteins with

strong T-cell epitopes would ensure that also the cellular arm of the immune response is activated and likely to contribute to protection. Such a vaccine would include a group 1, group 2, and B stalk component to ensure broad protection against all circulating human influenza virus strains as well as against potential pandemic subtypes. Since most humans, with the exception of very young children, have a preexisting immunity to influenza viruses, including low levels of antibodies to the stalk domain of the HA, it is possible that vaccination with a trivalent chimeric HA vaccine could sufficiently boost these titers to protective levels.

## 6.10 EXAMPLE 10: H3 STALK-BASED CHIMERIC HEMAGGLUTININ INFLUENZA VIRUS CONSTRUCTS PROTECT MICE FROM H7N9 CHALLENGE

**[00603]** This example demonstrates that subjects can be protected against novel H7N9 virus using chimeric HA constructs that do not possess an H7 head domain. This example also demonstrates that oil-in-water based adjuvant similar to those licensed for humans performed well with the chimeric HA vaccine candidates.

**[00604]** To study the importance of mucosal responses to protection, an experimental set up that induces both, mucosal and systemic immunity was applied, and compared to one that would only induce systemic immunity. Additionally, two adjuvants, polyI:C (PIC) -which has been successfully used in combination with cHAs in animals before -, and a generic oil-in-water (OIW) adjuvant were compared (Ott *et al.*, 2000. The Adjuvant MF59: A 10-Year Perspective, p. 211-228. In O'Hagan DT (ed.), Vaccine Adjuvants, vol. 42. Springer). The latter is similar to adjuvants that have been licensed for use in humans (Ott *et al.*, 2000. The Adjuvant MF59: A 10-Year Perspective, p. 211-228. In O'Hagan DT (ed.), Vaccine Adjuvants, vol. 42. Springer).

**[00605]** Animals (squares, N=10 per group, females 6-8 weeks old BALB/c mice) were primed with a DNA plasmid expressing a cH4/3 protein (H4 head derived from A/duck/Czech/56 on top of an H3 stalk domain derived from A/Perth/16/09) (Margine *et al.*, 2013. *J Virol* 87:10435-10446) via intramuscular electroporation with a TriGrid electroporation device (Ichor Medical Systems) (Fig. 43A). It is of note that DNA vaccination is not essential for induction of broad protection by cHA vaccination regimens. Vaccination with just proteins (no DNA) yielded results comparable to vaccination with DNA priming in earlier studies (Goff *et al.,* 2013. *PLoS One* 8:e79194). Three weeks post prime, animals received a recombinant

cH5/3 protein (H5 head derived from A/Vietnam/1203/04 on top of an H3 stalk derived from A/Perth/16/09) (Margine *et al.*, 2013. *J Virol* 87:10435-10446). Animals in one group received 5 μg of cH5/3 protein intranasally (i.n.) and 5 μg intramuscularly (i.m.) adjuvanted with 5 μg of PIC (high molecular weight, Invivogen) ('PIC i.n.+i.m.'). A second group only received the i.m. dose with PIC (5 μg HA in total) ('PIC i.m.'), while a third group received 5 ug of cH5/3 protein with a generic OIW based adjuvant ('OIW i.m.') (Fig. 43A). All mice were boosted a second time three weeks later with full length H3 protein using the same vaccination routes, adjuvants, and immunogen amounts, respectively (Fig. 43A). All recombinant proteins used for vaccination were expressed in the baculovirus expression system with a C-terminal T4 foldon trimerization domain and a hexahistidine tag to facilitate purification (Krammer *et al.,* 2012. *PLoS One* 7:e43603). The OIW adjuvant (20mM citrate, 0.5% polysorbate 80, pH 6.5, 0.5% span-85 (sorbitan trioleate), 4.3% squalene) was prepared as described before (Ott *et al.*, 2000. The Adjuvant MF59: A 10-Year Perspective, p. 211-228. In O'Hagan DT (ed.), Vaccine Adjuvants, vol. 42. Springer) (Fig. 44). Positive controls (circles, n=5) received one i.m. vaccination of formalin-inactivated A/Shanghai/1/13 H7N9 (SH1, 6:2 reassortant with HA and NA derived from A/Shanghai/1/13 and the internal genes from A/Puerto Rico/8/34) whole virus preparation. Negative controls (triangles, n=4-5) received a mock DNA vaccination followed by two boosts with bovine serum albumin (BSA) administered in the same amounts and route with the respective cHA vaccination regimens they were compared to. Four weeks after the last immunization, animals were bled and then challenged with 10 murine lethal doses 50 (mLD50) of SH1 virus. Weight loss was monitored over a period of 14 days and mice that lost more than 20 percent of their initial body weight were euthanized. Animals in the PIC i.n.+i.m. group lost an average of 10% of their initial body weight (Fig. 43B) as compared to 15% in the PIC i.m. group (Fig. 43C), suggesting that the mucosal immunity at the site of infection has a significant role in protection. Furthermore, the mice in the OIW i.m. group lost only 12% of their initial body weight on average (Fig. 43D), which is also reflected in the observed survival. All PIC i.m.+i.n. vaccinated animals survived the challenge (Fig. 43E), compared to only 70% of the PIC i.m. animals (Fig. 43F). However, survival in the OIW i.m. group was 100% (Fig. 43F), indicating a better protective effect with the OIW adjuvant. To quantitatively assess the titers of H7 HA antibodies elicited by the three different vaccination regimens, enzyme linked immunosorbent assays (ELISA) were performed using a recombinant SH1 H7 HA as substrate.

Since the cHA-vaccinated animals were not exposed to an H7 head domain, it was hypothesized that any observed reactivity to H7 would be predominantly derived from cross-reactive anti-stalk antibodies. To exclude binding to the hexahistidine tag or the trimerization domain, a recombinant SH1 H7 HA expressed with a GCN pII leucine zipper trimerization domain and a strep tag II was utilized (Krammer *et al.*, 2013. *J Virol* 87:6542-6550; Weldon *et al.*,. 2010. *PLoS One* 5.). The highest endpoint titers were detected in serum collected from PIC i.n.+i.m. vaccinated animals, followed by the OIW i.m. animals (Fig. 45A). Mice that received the PIC i.m. vaccine had statistically significant lower titers ($p=0.03$) than the OIW i.m. animals. This difference in endpoint titers correlates with the differences in weight loss and survival. The antibody isotype distribution can be strongly influenced by adjuvants and can have a high impact on the protective efficiency of antibodies. However, there were no significant differences in the isotype profile when the three vaccination regimens were compared (Fig. 45B). This suggests that–in the case of i.m. only vaccination–the antibody titer was the main correlate of protection. Sera from the vaccine and control groups were also tested in a micro-neutralization assay but results for the cHA vaccinated groups were negative, probably due to the limit of detection (1:20) of this assay (data not shown). It is hypothesized that mucosal IgA antibodies induced by the i.n. vaccination had a substantial contribution to protection, since animals immunized via both routes showed lower morbidity than animals that were only vaccinated intramuscularly. Differences in weight loss between the PIC i.n.+i.m. and the PIC i.m. group were statistically significant on day 7 ($p=0.0383$) and day 8 (0.0136) (unpaired t-test). However, it should be noted that these animals also received twice as much antigen as the i.m. only animals.

**[00606]** In conclusion, this example demonstrates that mice can be protected against the novel H7N9 virus using a stalk-based immunization regimen with cHA constructs that do not possess an H7 head domain. Furthermore, an oil-in-water based adjuvant similar to those licensed for use in humans (Ott *et al.*, 2000. The Adjuvant MF59: A 10-Year Perspective, p. 211-228. In O'Hagan DT (ed.), Vaccine Adjuvants, vol. 42. Springer; O'Hagan *et al.,* 2013. *Expert Rev Vaccines* 12:13-30) performed well with the cHA vaccine candidates, suggesting that this combination could also be considered for testing in humans. An HA stalk based vaccine providing universal influenza virus protection could replace strain specific seasonal vaccines and further enhance preparedness against potential pandemic influenza virus strains like H7N9.

**[00607]** All publications, patents and patent applications cited in this specification are herein incorporated by reference as if each individual publication or patent application were specifically and individually indicated to be incorporated by reference. Although the foregoing invention has been described in some detail by way of illustration and example for purposes of clarity of understanding, it will be readily apparent to those of ordinary skill in the art in light of the teachings of this invention that certain changes and modifications may be made thereto without departing from the spirit or scope of the appended claims.

**WHAT IS CLAIMED IS:**

1. A chimeric influenza virus hemagglutinin (HA) polypeptide comprising the stem domain of the HA from influenza virus A/California/4/2009 (H1N1) and the globular head domain of the HA from an influenza virus of the H5 subtype.

2. The chimeric influenza virus hemagglutinin (HA) polypeptide of claim 1, wherein the H5 subtype is influenza virus A/Vietnam/1203/2004 (H5), A/Indonesia/5/2005 (H5), A/Anhui/1/2005 (H5), A/bar headed goose/Quinghai/1A/2005 (H5), A/turkey/Turkey/1/2005 (H5), or A/whooperswan/Mongolia/244/2005 (H5).

3. A chimeric influenza virus hemagglutinin (HA) polypeptide comprising the stem domain of the HA from influenza virus A/Victoria/361/2011 (H3N2), A/harbor seal/Massachusetts/1/2011 (H3N8), or A/Indiana/10/2011 (H3N2) and the globular head domain of the HA from an influenza virus of the H5 subtype.

4. The chimeric influenza virus hemagglutinin (HA) polypeptide of claim 3, wherein the H5 subtype is influenza virus HA of A/Vietnam/1203/2004 (H5), A/Indonesia/5/2005 (H5), A/Anhui/1/2005 (H5), A/bar headed goose/Quinghai/1A/2005 (H5), A/turkey/Turkey/1/2005 (H5), or A/whooperswan/Mongolia/244/2005 (H5).

5. A chimeric influenza virus hemagglutinin (HA) polypeptide comprising the stem domain of the HA from influenza virus A/Victoria/361/2011 (H3N2), A/harbor seal/Massachusetts/1/2011 (H3N8), or A/Indiana/10/2011 (H3N2) and the globular head domain of the HA from an influenza virus of the H7 subtype.

6. The chimeric influenza virus hemagglutinin (HA) polypeptide of claim 5, wherein the H7 subtype is influenza virus A/Netherlands/219/03 (H7), A/Canada/504/04 (H7), A/Canada/444/04 (H7), A/chicken/Jalisco/CPA1/2012 (H7), A/mallard/Alberta/24/2001 (H7), A/rhea/NC/39482/93 (H7), or A/mallard/Netherlands/12/2000 (H7).

7. A chimeric influenza virus hemagglutinin (HA) polypeptide comprising the stem domain of the HA from influenza virus B/Malaysia/2506/2004, B/Florida/4/2006, B/Wisconsin/1/2010, or B/Brisbane/60/2008 and the globular head domain of the HA from an influenza virus of the H5 subtype.

8. The chimeric influenza virus hemagglutinin (HA) polypeptide of claim 7, wherein the H5 subtype is influenza virus A/Vietnam/1203/2004 (H5), A/Indonesia/5/2005 (H5), A/Anhui/1/2005 (H5), A/bar headed goose/Quinghai/1A/2005 (H5), A/turkey/Turkey/1/2005 (H5), or A/whooperswan/Mongolia/244/2005 (H5).

9. A chimeric influenza virus hemagglutinin (HA) polypeptide comprising the stem domain of the HA from influenza virus B/Malaysia/2506/2004, B/Florida/4/2006, B/Wisconsin/1/2010, or B/Brisbane/60/2008 and the globular head domain of the HA from an influenza virus of the H7 subtype.

10. The chimeric influenza virus hemagglutinin (HA) polypeptide of claim 9, wherein the H7 subtype is influenza virus A/Netherlands/219/03 (H7), A/Canada/504/04 (H7), A/Canada/444/04 (H7), A/chicken/Jalisco/CPA1/2012 (H7), A/mallard/Alberta/24/2001 (H7), A/rhea/NC/39482/93 (H7), or A/mallard/Netherlands/12/2000 (H7).

11. A chimeric influenza virus hemagglutinin (HA) polypeptide comprising the stem domain of the HA from influenza virus B/Malaysia/2506/2004, B/Florida/4/2006, B/Wisconsin/1/2010, or B/Brisbane/60/2008 and the globular head domain of the HA from a different strain of influenza B virus.

12. The chimeric influenza virus hemagglutinin (HA) polypeptide of claim 11, wherein the different strain of influenza B virus is B/Lee/1940 or B/seal/Netherlands/1/99.

13. A nucleic acid encoding the chimeric influenza virus hemagglutinin (HA) polypeptide of any one of claims 1 to 12.

14. A cell expressing the nucleic acid of claim 13.

15. A virus comprising a genome engineered to express the nucleic acid of claim 13.

16. A virus comprising the polypeptide of any one of claims 1 to 12.

17. The virus of claim 15, wherein the virus is an influenza virus, VSV, NDV, adenovirus, or baculovirus.

18. The virus of claim 16, wherein the virus is an influenza virus, VSV, NDV, adenovirus, or baculovirus.

19. The virus of claim 17, which is inactivated or split.

20. The virus of claim 18, which is inactivated or split.

21. A virus-like particle comprising the polypeptide of any one of claims 1 to 12.

22. An immunogenic composition comprising the polypeptide of any one of claims 1 to 12.

23. An immunogenic composition comprising the virus of claim 15.

24. An immunogenic composition comprising the virus of claim 16.

25. An immunogenic composition comprising the virus of claim 17.

26. An immunogenic composition comprising the virus of claim 18.

27. An immunogenic composition comprising the virus-like particle of claim 21.

28. An immunogenic composition comprising:

(i) a first chimeric influenza virus hemagglutinin (HA) polypeptide, wherein the polypeptide comprises the stem domain of the HA of influenza virus A/California/4/2009 (H1N1) and the globular head domain of the HA of influenza virus /Vietnam/1203/2004 (H5),

A/Indonesia/5/2005 (H5), A/Anhui/1/2005 (H5), A/bar headed goose/Quinghai/1A/2005 (H5), A/turkey/Turkey/1/2005 (H5), or A/whooperswan/Mongolia/244/2005 (H5); and

(ii) a second chimeric influenza virus hemagglutinin (HA) polypeptide, wherein the polypeptide comprises (a) the stem domain of the HA of influenza virus A/Victoria/361/2011 (H3N2), A/harbor seal/Massachusetts/1/2011 (H3N8), or A/Indiana/10/2011 (H3N2); and (b) the globular head domain of the HA of influenza virus A/Vietnam/1203/2004 (H5), A/Indonesia/5/2005 (H5), A/Anhui/1/2005 (H5), A/bar headed goose/Quinghai/1A/2005 (H5), A/turkey/Turkey/1/2005 (H5), or A/whooperswan/Mongolia/244/2005 (H5).

29. An immunogenic composition comprising:

(i) a first chimeric influenza virus hemagglutinin (HA) polypeptide, wherein the polypeptide comprises the stem domain of the HA of influenza virus A/California/4/2009 (H1N1) and the globular head domain of the HA of influenza virus A/Vietnam/1203/2004 (H5), A/Indonesia/5/2005 (H5), A/Anhui/1/2005 (H5), A/bar headed goose/Quinghai/1A/2005 (H5), A/turkey/Turkey/1/2005 (H5), or A/whooperswan/Mongolia/244/2005 (H5); and

(ii) a second chimeric influenza virus hemagglutinin (HA) polypeptide, wherein the polypeptide comprises (a) the stem domain of the HA of influenza virus A/Victoria/361/2011 (H3N2), A/harbor seal/Massachusetts/1/2011 (H3N8), or A/Indiana/10/2011 (H3N2); and (b) the globular head domain of the HA of influenza virus B/Malaysia/2506/2004 and the globular head domain of the HA of influenza virus A/Netherlands/219/03 (H7), A/Canada/504/04 (H7), A/Canada/444/04 (H7), A/chicken/Jalisco/CPA1/2012 (H7), A/mallard/Alberta/24/2001 (H7), A/rhea/NC/39482/93 (H7), or A/mallard/Netherlands/12/2000 (H7).

30. The immunogenic composition of claim 28 or 29, further comprising a third chimeric influenza virus hemagglutinin (HA) polypeptide, wherein the polypeptide comprises (a) the stem domain of the HA of influenza virus B/Malaysia/2506/2004, B/Florida/4/2006, B/Wisconsin/1/2010; or B/Brisbane/60/2008; and (b) the globular head domain of the HA of influenza virus A/Vietnam/1203/2004 (H5), A/Indonesia/5/2005 (H5), A/Anhui/1/2005 (H5), A/bar headed goose/Quinghai/1A/2005 (H5), A/turkey/Turkey/1/2005 (H5), A/whooperswan/Mongolia/244/2005 (H5), B/Lee/1940, or B/Seal/Netherlands/1/99.

31. An immunogenic composition comprising:

(i) a first virus comprising a genome engineered to express a first nucleic acid that encodes a chimeric influenza virus hemagglutinin (HA) polypeptide, wherein the polypeptide comprises the stem domain of the HA of influenza virus A/California/4/2009 (H1N1) and the globular head domain of the HA of influenza virus A/Vietnam/1203/2004 (H5), A/Indonesia/5/2005 (H5), A/Anhui/1/2005 (H5), A/bar headed goose/Quinghai/1A/2005 (H5), A/turkey/Turkey/1/2005 (H5), or A/whooperswan/Mongolia/244/2005 (H5); and

(ii) a second virus comprising a genome engineered to express a second nucleic acid that encodes a chimeric influenza virus hemagglutinin (HA) polypeptide, wherein the polypeptide comprises (a) the stem domain of the HA of influenza virus A/Victoria/361/2011 (H3N2), A/harbor seal/Massachusetts/1/2011 (H3N8), or A/Indiana/10/2011 (H3N2); and (b) the globular head domain of the HA of influenza virus A/Vietnam/1203/2004 (H5), A/Indonesia/5/2005 (H5), A/Anhui/1/2005 (H5), A/bar headed goose/Quinghai/1A/2005 (H5), A/turkey/Turkey/1/2005 (H5), or A/whooperswan/Mongolia/244/2005 (H5).

32. An immunogenic composition comprising:

(i) a first virus comprising a genome engineered to express a first nucleic acid that encodes a chimeric influenza virus hemagglutinin (HA) polypeptide, wherein the polypeptide comprises the stem domain of the HA of influenza virus A/California/4/2009 (H1N1) and the globular head domain of the HA of influenza virus A/Vietnam/1203/2004 (H5), A/Indonesia/5/2005 (H5), A/Anhui/1/2005 (H5), A/bar headed goose/Quinghai/1A/2005 (H5), A/turkey/Turkey/1/2005 (H5), or A/whooperswan/Mongolia/244/2005 (H5); and

(ii) a second virus comprising a genome engineered to express a second nucleic acid that encodes a chimeric influenza virus hemagglutinin (HA) polypeptide, wherein the polypeptide comprises (a) the stem domain of the HA of influenza virus A/Victoria/361/2011 (H3N2), A/harbor seal/Massachusetts/1/2011 (H3N8), or A/Indiana/10/2011 (H3N2); and (b) the globular head domain of the HA of influenza virus B/Malaysia/2506/2004 and the globular head domain of the HA of A/Netherlands/219/03 (H7), A/Canada/504/04 (H7), A/Canada/444/04 (H7), A/chicken/Jalisco/CPA1/2012 (H7), A/mallard/Alberta/24/2001 (H7), A/rhea/NC/39482/93 (H7), or A/mallard/Netherlands/12/2000 (H7).

33. The immunogenic composition of claim 31 or 32, further comprising a third virus comprising a genome engineered to express a third nucleic acid that encodes a chimeric influenza virus hemagglutinin (HA) polypeptide, wherein the polypeptide comprises (a) the stem domain of the HA of influenza virus B/Malaysia/2506/2004, B/Florida/4/2006, B/Wisconsin/1/2010; or B/Brisbane/60/2008; and (b) the globular head domain of the HA of influenza virus A/Vietnam/1203/2004 (H5), A/Indonesia/5/2005 (H5), A/Anhui/1/2005 (H5), A/bar headed goose/Quinghai/1A/2005 (H5), A/turkey/Turkey/1/2005 (H5), A/whooperswan/Mongolia/244/2005 (H5), B/Lee/1940, or B/Seal/Netherlands/1/99.

34. An immunogenic composition comprising:

(i) a first virus comprising a first chimeric influenza virus hemagglutinin (HA) polypeptide, wherein the polypeptide comprises the stem domain of the HA of influenza virus A/California/4/2009 (H1N1) and the globular head domain of the HA of influenza virus A/Vietnam/1203/2004 (H5), A/Indonesia/5/2005 (H5), A/Anhui/1/2005 (H5), A/bar headed goose/Quinghai/1A/2005 (H5), A/turkey/Turkey/1/2005 (H5), or A/whooperswan/Mongolia/244/2005 (H5); and

(ii) a second virus comprising a second chimeric influenza virus hemagglutinin (HA) polypeptide, wherein the polypeptide comprises (a) the stem domain of the HA of influenza virus A/Victoria/361/2011 (H3N2), A/harbor seal/Massachusetts/1/2011 (H3N8), or A/Indiana/10/2011 (H3N2); and (b) the globular head domain of the HA of influenza virus A/Vietnam/1203/2004 (H5), A/Indonesia/5/2005 (H5), A/Anhui/1/2005 (H5), A/bar headed goose/Quinghai/1A/2005 (H5), A/turkey/Turkey/1/2005 (H5), or A/whooperswan/Mongolia/244/2005 (H5).

35. An immunogenic composition comprising:

(i) a first virus comprising a first chimeric influenza virus hemagglutinin (HA) polypeptide, wherein the polypeptide comprises the stem domain of the HA of influenza virus A/California/4/2009 (H1N1) and the globular head domain of the HA of influenza virus A/Vietnam/1203/2004 (H5), A/Indonesia/5/2005 (H5), A/Anhui/1/2005 (H5), A/bar headed goose/Quinghai/1A/2005 (H5), A/turkey/Turkey/1/2005 (H5), or A/whooperswan/Mongolia/244/2005 (H5); and

(ii) a second virus comprising a second chimeric influenza virus hemagglutinin (HA) polypeptide, wherein the polypeptide comprises (a) the stem domain of the HA of influenza virus A/Victoria/361/2011 (H3N2), A/harbor seal/Massachusetts/1/2011 (H3N8), or A/Indiana/10/2011 (H3N2); and (b) the globular head domain of the HA of influenza virus A/Netherlands/219/03 (H7), A/Canada/504/04 (H7), A/Canada/444/04 (H7), A/chicken/Jalisco/CPA1/2012 (H7), A/mallard/Alberta/24/2001 (H7), A/rhea/NC/39482/93 (H7), or A/mallard/Netherlands/12/2000 (H7); and

36. The immunogenic composition of claim 34 or 35, further comprising a third virus comprising a third chimeric influenza virus hemagglutinin (HA) polypeptide, wherein the polypeptide comprises (a) the stem domain of the HA of influenza virus B/Malaysia/2506/2004, B/Florida/4/2006, B/Wisconsin/1/2010; or B/Brisbane/60/2008; and (b) the globular head domain of the HA of influenza virus A/Vietnam/1203/2004 (H5), A/Indonesia/5/2005 (H5), A/Anhui/1/2005 (H5), A/bar headed goose/Quinghai/1A/2005 (H5), A/turkey/Turkey/1/2005 (H5), A/whooperswan/Mongolia/244/2005 (H5), B/Lee/1940, or B/Seal/Netherlands/1/99.

37. The immunogenic composition of any one of claims 31-36, wherein each of the viruses in the immunogenic composition is an influenza virus, VSV, NDV, or adenovirus.

38. The immunogenic composition of any one of claims 31-36, wherein each of the viruses in the immunogenic composition is inactivated or split.

39. The immunogenic composition of claim 37, wherein each of the influenza viruses is inactivated or split.

40. A method of immunizing a subject against influenza virus comprising administering to the subject an effective amount of the immunogenic composition of any one of claims 22-39.

41. A method of immunizing a subject against influenza virus comprising administering to the subject a first dose of an effective amount of an immunogenic composition and administering to the subject a second dose of an effective amount of the immunogenic

composition 30 days to 6 months after the subject has received the first dose, wherein the immunogenic composition is the composition of any one of claims 22-39.

42. The method of claim 41, further comprising administering to the subject a third dose of an effective amount of the immunogenic composition 30 days to 6 months after the subject has received the second dose.

43. A method of immunizing a subject against influenza virus comprising administering to the subject a first dose of an effective amount of a first immunogenic composition and administering to the subject a second dose of an effective amount of a second immunogenic composition 30 days to 6 months after the subject has received the first dose, wherein the immunogenic compositions are the compositions of any one of claims 22-39, and wherein the globular head domain of the chimeric influenza virus hemagglutinin (HA) polypeptide present in the first immunogenic composition is different than the globular head domain of the chimeric influenza virus hemagglutinin (HA) polypeptide present in the second immunogenic composition.

44. A method of preventing an influenza virus disease comprising administering to a subject an effective amount of the immunogenic composition of any one of claims 22-39.

45. A method of treating an influenza virus infection or an influenza virus disease comprising administering to a subject an effective amount of the immunogenic composition of any one of claims 22-39.

46. The method of any one of claims 40-45, wherein the subject is a human.

47. The method of claim 41 or 43, wherein the subject is a 1-5 year old human subject.

48. The method of claim 41 or 43, wherein the subject is an elderly human subject.

49. The method of any one of claims 40-48, wherein the immunogenic composition is administered intramuscularly or intranasally to the subject.

50. The chimeric influenza virus hemagglutinin (HA) polypeptide of any one of claims 1 to 12, wherein the polypeptide is soluble.

51. The chimeric influenza virus hemagglutinin (HA) polypeptide of claim 50, wherein the polypeptide comprises a trimerization domain.

52. The immunogenic composition of any one of claims 22-39 for use in a method of immunizing a subject against influenza virus.

53. The immunogenic composition of any one of claims 22-39 for use in a method of immunizing a subject against influenza virus, wherein said method comprises administering to the subject a first dose of an effective amount of an immunogenic composition and administering to the subject a second dose of an effective amount of the immunogenic composition 30 days to 6 months after the subject has received the first dose.

54. The immunogenic composition of claim 53, wherein said method further comprises administering to the subject a third dose of an effective amount of the immunogenic composition 30 days to 6 months after the subject has received the second dose.

55. The immunogenic composition of any one of claims 22-39 for use in a method of immunizing a subject against influenza virus, wherein said method comprises administering to the subject a first dose of an effective amount of a first immunogenic composition and administering to the subject a second dose of an effective amount of a second immunogenic composition 30 days to 6 months after the subject has received the first dose, and wherein the globular head domain of the chimeric influenza virus hemagglutinin (HA) polypeptide present in the first immunogenic composition is different than the globular head domain of the chimeric influenza virus hemagglutinin (HA) polypeptide present in the second immunogenic composition.

56. The immunogenic composition of any one of claims 22-39 for use in a method of preventing an influenza virus disease in a subject.

57. The immunogenic composition of any one of claims 22-39 for use in a method of treating an influenza virus infection or an influenza virus disease in a subject.

58. The immunogenic composition of any one of claims 52-57, wherein the subject is a human.

59. Use of the immunogenic composition of any one of claims 22-39 for the manufacture of a medicament for use in a method of immunizing a subject against influenza virus.

60. Use of the immunogenic composition of any one of claims 22-39 for the manufacture of a medicament for use in a method of immunizing a subject against influenza virus, wherein said method comprises administering to the subject a first dose of an effective amount of an immunogenic composition and administering to the subject a second dose of an effective amount of the immunogenic composition 30 days to 6 months after the subject has received the first dose.

61. The use of claim 60, wherein said method further comprises administering to the subject a third dose of an effective amount of the immunogenic composition 30 days to 6 months after the subject has received the second dose.

62. Use of the immunogenic composition of any one of claims 22-39 for the manufacture of a medicament for use in a method of immunizing a subject against influenza virus, wherein said method comprises administering to the subject a first dose of an effective amount of a first immunogenic composition and administering to the subject a second dose of an effective amount of a second immunogenic composition 30 days to 6 months after the subject has received the first dose, and wherein the globular head domain of the chimeric influenza virus hemagglutinin (HA) polypeptide present in the first immunogenic composition is different than

the globular head domain of the chimeric influenza virus hemagglutinin (HA) polypeptide present in the second immunogenic composition.

63. Use of the immunogenic composition of any one of claims 22-39 for the manufacture of a medicament for use in a method of preventing an influenza virus disease in a subject.

64. Use of the immunogenic composition of any one of claims 22-39 for the manufacture of a medicament for use in a method of treating an influenza virus infection or an influenza virus disease in a subject.

65. Use of the immunogenic composition of any one of claims 59-64, wherein the subject is human.