

VIRUS LIKE PARTICLE COMPOSITIONS AND METHODS OF USE

CROSS-REFERENCE TO RELATED APPLICATION

This application claims the benefit of the following U.S. Provisional Application
5 Nos.: 61/118,206 and 61/201,118, filed on November 26, 2008 and December 5, 2008,
respectively, the entire contents of each of which are incorporated herein by reference.

STATEMENT OF RIGHTS TO INVENTIONS MADE UNDER FEDERALLY SPONSORED RESEARCH

10 Research supporting this application was carried out by the United States of America
as represented by the Secretary, Department of Health and Human Services. This research
was supported by the Intramural Research Program, Vaccine Research Center, NIAID of the
National Institute of Health. The Government has certain rights in this invention.

BACKGROUND OF THE INVENTION

Chikungunya virus (CHIKV), a mosquito-borne alphavirus in the family Togaviridae,
was first isolated in Tanzania in 1952. Infection by this virus causes human disease that is
characterized by rash, high fever and, its hallmark feature, severe arthritis that can persist for
years. Chikungunya virus (CHIKV) has infected millions of people in Africa, Europe, and Asia since
20 its re-emergence in Kenya in 2004. The evolution and spread of the virus into new geographic areas,
and the disease severity present a serious public health in the absence of a vaccines or anti-viral
therapies. Therefore, the development of anti-viral therapies for CHIKV and vaccine
development remains a high priority. Phylogenetic analysis of CHIKV showed that there are
three genotypes: Asian, East/Central/South African and West African. The Asian and
25 East/Central/South African genotypes are most similar, whereas the West African strains are
more divergent. Therapeutic and/or prophylactic methods for treating or preventing
Chikungunya viral disease are urgently required.

SUMMARY OF THE INVENTION

As described below, the present invention features compositions and methods for the
30 prevention or treatment of one or more strains of Chikungunya virus, as well as other
alphavirus-mediated diseases.

In one aspect, the invention provides a virus-like particle (VLP) containing one or
more (e.g., one, two, three, four, five) Chikungunya virus structural polypeptides. In one

embodiment, the structural polypeptides are any one or more of capsid and envelope proteins E3, E2, 6K and E1.

In another aspect, the invention provides an isolated polynucleotide encoding a virus-like particle of the previous aspect or any other VLP delineated herein. In one embodiment, the polynucleotide encodes a Chikungunya virus polyprotein containing C-E3-E2-6K-E1.

In a related aspect, the invention provides an expression vector containing a polynucleotide encoding one or more Chikungunya virus structural polypeptides.

In another aspect, the invention provides a prokaryotic or eukaryotic cell (e.g., mammalian, human, insect) containing the expression vector of any previous aspect or any other expression vector delineated herein. In one embodiment, the cell is *in vitro*.

In another aspect, the invention provides an immunogenic composition containing an effective amount of a virus-like particle of any previous aspect or any other VLP delineated herein.

In a related aspect, the invention provides an immunogenic composition containing an effective amount of a VLP containing a Chikungunya structural polyprotein containing C-E3-E2-6K-E1 and an adjuvant.

In another aspect, the invention provides an immunogenic composition containing an effective amount of an expression vector of any previous aspect or otherwise delineated herein (e.g., a DNA vaccine).

In another aspect, the invention provides a vaccine containing an effective amount of one or more Chikungunya virus structural polypeptides that is any one or more of capsid (C) and envelope proteins E1, E2, E3 and 6K.

In another aspect, the invention provides a vaccine containing an effective amount of a virus-like particle of any previous aspect or containing a polyprotein containing C-E3-E2-6K-E1.

In another aspect, the invention provides a vaccine containing a polynucleotide encoding a Chikungunya structural polyprotein or fragment thereof. In one embodiment, the Chikungunya structural polyprotein is encoded by an expression vector of any previous aspect. In one embodiment, the expression vector comprises a CMV/R promoter. In another embodiment, the vaccine is a DNA vaccine.

In another aspect, the invention provides a method of inducing an immune response against Chikungunya in a subject (e.g. human), the method involving administering to the subject an effective amount of an immunogenic composition of any previous aspect or any other immunogenic composition delineated herein. In one embodiment, the immunogenic

composition contains one or more Chikungunya virus structural polypeptides that is any one or more of capsid (C) and envelope proteins E1, E2, E3 and 6K. In another embodiment, the immunogenic composition comprises a polyprotein containing C-E3-E2-6K-E1. In another embodiment, the method induces neutralizing antibodies in a subject.

5 In another aspect, the invention provides a method for treating or preventing a Chikungunya infection in a subject, the method involving administering to the subject an effective amount of a vaccine of any previous aspect or an immunogenic composition of any previous aspect. In one embodiment, wherein the vaccine or immunogenic composition is administered in one or more doses.

10 In another aspect, the invention provides a method for producing a virus-like particle, the method involves expressing in a cell one or more Chikungunya structural protein capable of self-assembly to form a virus-like particle. In one embodiment, the method further involves isolating the virus-like particle.

 In another aspect, the invention provides a virus-like particle (VLP) containing one or
15 more alphavirus structural polypeptides (e.g., capsid or envelope polypeptide). In one embodiment, the alphavirus is any one or more of Chikungunya virus, Sindbis virus, Eastern equine encephalitis (EEE) virus, Western equine encephalitis (WEE) virus, and Venezuelan equine encephalitis (VEE) virus.

 In another aspect, the invention provides an isolated polynucleotide encoding a virus-
20 like particle of the previous aspect or otherwise delineated herein.

 In another aspect, the invention provides an expression vector containing a polynucleotide encoding one or more alphavirus structural polypeptides wherein the alphavirus is selected from the group consisting of Chikungunya virus, Sindbis virus, Eastern equine encephalitis (EEE) virus, Western equine encephalitis (WEE) virus, and Venezuelan
25 equine encephalitis (VEE) virus.

 In another aspect, the invention provides an immunogenic composition containing an effective amount of a virus-like particle of any previous aspect or otherwise delineated herein.

 In another aspect, the invention provides a vaccine containing an effective amount of
30 one or more alphavirus structural polypeptides or a polynucleotide encoding one or more alphavirus structural proteins, wherein the alphavirus is selected from the group consisting of Chikungunya virus, Sindbis virus, Eastern equine encephalitis (EEE) virus, Western equine encephalitis (WEE) virus, and Venezuelan equine encephalitis (VEE) virus.

In another aspect, the invention provides a method of inducing an immune response against an alphavirus in a subject, the method involving administering to the subject an effective amount of an immunogenic composition of a previous aspect. In one embodiment, the immunogenic composition contains one or more alphavirus structural polypeptides (e.g. envelope or capsid).

In another aspect, the invention provides a method for treating or preventing an alphavirus infection in a subject, the method involving administering to the subject an effective amount of a vaccine or an immunogenic composition of any previous aspect.

In another aspect, the invention provides a kit containing a VLP of any previous aspect, and instructions for use.

In another aspect, the invention provides a kit containing an immunogenic composition of any previous aspect, and instructions for use in a subject. In one embodiment, the immunogenic composition is provided in a first container and a second immunogenic composition is provided in a second container, and instructions for use in a prime boost immunization. In another embodiment, the immunogenic composition in the second container contains a VLP, viral polypeptide, or viral polynucleotide.

In another aspect, the invention provides a method for identifying inhibitors of Chikungunya virus entry into a eukaryotic cell, the method involving contacting a cell that expresses a Chikungunya virus receptor with a Chikungunya polypeptide selected from the group consisting of C, E3, E2, 6K, and E1 and a candidate compound, and assaying for viral entry, wherein a candidate compound that reduces viral entry in the cell relative to a control cell is identified as an inhibitor of Chikungunya virus entry. In one embodiment, the candidate inhibitor is an antibody, or fragment thereof or small molecule.

In another aspect, the invention provides a method for identifying inhibitors of Chikungunya viral entry involving contacting a cell that expresses a Chikungunya virus receptor with a candidate inhibitor and a pseudotyped virus containing a reporter gene; and measuring expression of the reporter gene in the cell, wherein a compound that reduces expression of the reporter gene relative to a control cell is identified as inhibiting viral entry. In one embodiment, the pseudotyped virus (e.g., lentivirus) contains one or more Chikungunya virus envelope proteins (e.g., E3, E2, 6K and E1). In one embodiment, the candidate inhibitor is an antibody, or fragment thereof or small molecule.

In another aspect, the invention provides a virus-like particle (VLP) containing one or more Chikungunya virus structural polypeptides for use in treating or preventing a Chikungunya infection.

In another aspect, the invention provides a method for treating or preventing a Chikungunya infection, the method involving administering a virus-like particle (VLP) containing one or more Chikungunya virus structural polypeptides prior to, subsequent to, concurrent with, or in any other sequence with the administration of one or more of another immunogenic composition, antiviral, or antibiotic agent.

In another aspect, the invention provides methods for treating or preventing a Chikungunya infection by administering neutralizing antibodies (e.g., mammalian, human) generated against a VLP of the invention to a subject (e.g., human).

In various embodiments of the above aspects or any other aspect of the invention delineated herein, the VLP contains one or more (1, 2, 3, 4) envelop proteins E3, E2, 6K and E1. In other embodiments, the VLP contains a polyprotein containing C-E3-E2-6K-E1 or a fragment thereof. In other embodiments of the above aspects or any other aspect of the invention delineated herein, a polynucleotide encodes one or more structural polypeptides that is any one or more of a alphavirus or Chikungunya virus capsid (C) and envelope proteins E3, E2, 6K and E1. In other embodiments, the polynucleotide encodes envelop proteins E3, E2, 6K and E1. In other embodiments, the polynucleotide encodes a Chikungunya virus polyprotein containing C-E3-E2-6K-E1. In still other embodiments, the expression vector is capable of expression in a prokaryotic or eukaryotic cell (e.g., mammal, human). In other embodiments, the structural polyprotein is derived from Chikungunya strain 37997 or LR2006. In other embodiments, the vector comprises the CMV/R promoter. In other embodiments, the expression vector is C-E37997 or C-EOPY-1. In other embodiments, the VLP induces an immune response (e.g., a protective immune response) in a subject. In other embodiments, the immune response treats or prevents a Chikungunya infection in a subject. In other embodiments of the above aspects, the VLP induces antibodies against homologous or heterologous strains of Chikungunya. In embodiments of the above aspects, the adjuvant is an immunostimulating agent (e.g., Ribi, aluminum salts, muramyl peptides, bacterial cell wall components, saponin adjuvants). In other embodiments of the above aspects, the vaccine or immunogenic composition is administered in one or more priming immunizations and one or more boosting immunizations. In still another embodiment, the priming immunizations are administered at one, two, three, four, five, six, seven or eight week intervals. In still another embodiment, the boosting immunizations are administered two weeks, one month, two months or three months after the priming immunization. In other embodiments of the above aspects or any other aspect of the invention delineated herein, the immunization protects the subject against

viremia or the inflammatory consequences of infection. In other embodiments, the method protects a subject from lethality. In other embodiments, the method induces neutralizing antibodies in the subject.

The invention provides immunogenic compositions featuring virus-like particles comprising Chikungunya polypeptides for the prevention or treatment of Chikungunya viral disease. Compositions and articles defined by the invention were isolated or otherwise manufactured in connection with the examples provided below. Other features and advantages of the invention will be apparent from the detailed description, and from the claims.

10

Definitions

By "alphavirus structural protein" is meant a polypeptide or fragment thereof having at least about 40% amino acid sequence identity to a naturally occurring viral capsid or envelope protein and having immunogenic activity in a mammal. In one embodiment, the alphavirus structural protein has at least about 85%, 90%, 95% or greater amino acid sequence identity with a Chikungunya virus structural protein or immunogenic fragment thereof. In one embodiment, the protein Exemplary alphaviruses include, but are not limited to, Western, Eastern, and Venezuelan equine encephalitis viruses, o'nyong-nyong virus, Ross River virus and Sindbis virus.

By "Chikungunya virus structural protein" is meant a polypeptide or fragment thereof having at least about 85% amino acid sequence identity to a naturally occurring Chikungunya virus capsid or envelope protein. In other embodiments, the amino acid sequence identity is at least about 90%, 95%, or more.

By "agent" is meant any small molecule chemical compound, antibody, nucleic acid molecule, or polypeptide, or fragments thereof.

As used herein, the term "adjuvant" is meant to refer to a compound that, when used in combination with a specific immunogen in a formulation, will augment, alter or modify the resultant immune response. In certain embodiments, the adjuvant is used in combination with a VLP. In other embodiments, the adjuvant is used in combination with a DNA vaccine. Modification of the immune response includes intensification or broadening the specificity of either or both antibody and cellular immune responses. Modification of the immune response can also mean decreasing or suppressing certain antigen-specific immune responses. In one embodiment, the adjuvant is Ribi adjuvant.

As used herein "alphavirus" is meant to refer to RNA-containing viruses that belong to the group IV Togaviridae family of viruses. Exemplary alphaviruses include but are not limited to Western, Eastern, and Venezuelan equine encephalitis viruses, o'nyong-nyong virus, Ross River virus and Sindbis virus.

5 As used herein "inducing immunity" is meant to refer to any immune response generated against an antigen. In one embodiment, immunity is mediated by antibodies against an infectious agent, which is exhibited by a vertebrate (e.g., a human), that prevents or ameliorates an infection or reduces at least one symptom thereof. VLPs or DNA vaccines of the invention can stimulate the production of antibodies that, for example, neutralize
10 infectious agents, block infectious agents from entering cells, block replication of infectious agents, and/or protect host cells from infection and destruction. The term can also refer to an immune response that is mediated by T-lymphocytes and/or other white blood cells against an infectious agent, exhibited by a vertebrate (e.g., a human), that prevents or ameliorates an infection, for example CHIKV infection, or reduces at least one symptom thereof.

15 By "ameliorate" is meant decrease, suppress, attenuate, diminish, arrest, or stabilize the development or progression of a disease or a symptom thereof.

By "alteration" is meant a change (increase or decrease) in the expression levels or activity of a gene or polypeptide as detected by standard art known methods such as those described herein. As used herein, an alteration includes a 10% change in expression levels,
20 preferably a 25% change, more preferably a 40% change, and most preferably a 50% or greater change in expression levels. "

By "analog" is meant a molecule that is not identical, but has analogous functional or structural features. For example, a polypeptide analog retains the biological activity of a corresponding naturally-occurring polypeptide, while having certain biochemical
25 modifications that enhance the analog's function relative to a naturally occurring polypeptide. Such biochemical modifications could increase the analog's protease resistance, membrane permeability, or half-life, without altering, for example, ligand binding. An analog may include an unnatural amino acid.

In this disclosure, "comprises," "comprising," "containing" and "having" and the like
30 can have the meaning ascribed to them in U.S. Patent law and can mean "includes," "including," and the like; "consisting essentially of" or "consists essentially" likewise has the meaning ascribed in U.S. Patent law and the term is open-ended, allowing for the presence of more than that which is recited so long as basic or novel characteristics of that which is

recited is not changed by the presence of more than that which is recited, but excludes prior art embodiments.

"Detect" refers to identifying the presence, absence or amount of the analyte to be detected.

5 By "disease" is meant any condition or disorder that damages or interferes with the normal function of a cell, tissue, or organ. Examples of diseases include viral infections including but not limited to Western, Eastern, and Venezuelan equine encephalitis viruses, o'nyong-nyong virus, Ross River virus and Sindbis virus.

10 By "effective amount" is meant the amount of an agent required to ameliorate the symptoms of a disease relative to an untreated patient. The effective amount of active compound(s) used to practice the present invention for prevention or treatment of a disease varies depending upon the manner of administration, the age, body weight, and general health of the subject. Ultimately, the attending physician or veterinarian will decide the appropriate amount and dosage regimen. Such amount is referred to as an "effective" amount.

15 The invention provides a number of targets that are useful for the development of highly specific drugs to treat or prevent a diseases delineated herein. In addition, the methods of the invention provide a facile means to identify therapies that are safe for use in subjects. In addition, the methods of the invention provide a route for analyzing virtually any number of compounds for effects on a disease described herein with high-volume throughput, high
20 sensitivity, and low complexity.

By "fragment" is meant a portion of a polypeptide or nucleic acid molecule. This portion contains, preferably, at least 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, or 90% of the entire length of the reference nucleic acid molecule or polypeptide. A fragment may contain 10, 20, 30, 40, 50, 60, 70, 80, 90, or 100, 200, 300, 400, 500, 600, 700, 800, 900, or
25 1000 nucleotides or amino acids.

"Hybridization" means hydrogen bonding, which may be Watson-Crick, Hoogsteen or reversed Hoogsteen hydrogen bonding, between complementary nucleobases. For example, adenine and thymine are complementary nucleobases that pair through the formation of hydrogen bonds.

30 By "isolated polynucleotide" is meant a nucleic acid molecule (e.g., a DNA) that is free of the genes which, in the naturally-occurring genome of the organism from which the nucleic acid molecule of the invention is derived, flank the gene. The term therefore includes, for example, a recombinant DNA that is incorporated into a vector; into an autonomously replicating plasmid or virus; or into the genomic DNA of a prokaryote or

eukaryote; or that exists as a separate molecule (for example, a cDNA or a genomic or cDNA fragment produced by PCR or restriction endonuclease digestion) independent of other sequences. In addition, the term includes an RNA molecule that is transcribed from a DNA molecule, as well as a recombinant DNA that is part of a hybrid gene encoding additional polypeptide sequence.

By an "isolated polypeptide" is meant a polypeptide of the invention that has been separated from components that naturally accompany it. Typically, the polypeptide is isolated when it is at least 60%, by weight, free from the proteins and naturally-occurring organic molecules with which it is naturally associated. Preferably, the preparation is at least 75%, more preferably at least 90%, and most preferably at least 99%, by weight, a polypeptide of the invention. An isolated polypeptide of the invention may be obtained, for example, by extraction from a natural source, by expression of a recombinant nucleic acid encoding such a polypeptide; or by chemically synthesizing the protein. Purity can be measured by any appropriate method, for example, column chromatography, polyacrylamide gel electrophoresis, or by HPLC analysis.

By "marker" is meant any protein or polynucleotide having an alteration in expression level or activity that is associated with a disease or disorder.

As used herein, "obtaining" as in "obtaining an agent" includes synthesizing, purchasing, or otherwise acquiring the agent.

By "reduces" is meant a negative alteration of at least 10%, 25%, 50%, 75%, or 100%.

By "reference" is meant a standard or control condition.

A "reference sequence" is a defined sequence used as a basis for sequence comparison. A reference sequence may be a subset of or the entirety of a specified sequence; for example, a segment of a full-length cDNA or gene sequence, or the complete cDNA or gene sequence. For polypeptides, the length of the reference polypeptide sequence will generally be at least about 16 amino acids, preferably at least about 20 amino acids, more preferably at least about 25 amino acids, and even more preferably about 35 amino acids, about 50 amino acids, or about 100 amino acids. For nucleic acids, the length of the reference nucleic acid sequence will generally be at least about 50 nucleotides, preferably at least about 60 nucleotides, more preferably at least about 75 nucleotides, and even more preferably about 100 nucleotides or about 300 nucleotides or any integer thereabout or therebetween.

By "specifically binds" is meant a compound or antibody that recognizes and binds a polypeptide of the invention, but which does not substantially recognize and bind other molecules in a sample, for example, a biological sample, which naturally includes a polypeptide of the invention.

5 Nucleic acid molecules useful in the methods of the invention include any nucleic acid molecule that encodes a polypeptide of the invention or a fragment thereof. Such nucleic acid molecules need not be 100% identical with an endogenous nucleic acid sequence, but will typically exhibit substantial identity. Polynucleotides having "substantial identity" to an endogenous sequence are typically capable of hybridizing with at least one
10 strand of a double-stranded nucleic acid molecule. Nucleic acid molecules useful in the methods of the invention include any nucleic acid molecule that encodes a polypeptide of the invention or a fragment thereof. Such nucleic acid molecules need not be 100% identical with an endogenous nucleic acid sequence, but will typically exhibit substantial identity. Polynucleotides having "substantial identity" to an endogenous sequence are typically
15 capable of hybridizing with at least one strand of a double-stranded nucleic acid molecule. By "hybridize" is meant pair to form a double-stranded molecule between complementary polynucleotide sequences (e.g., a gene described herein), or portions thereof, under various conditions of stringency. (See, e.g., Wahl, G. M. and S. L. Berger (1987) *Methods Enzymol.* 152:399; Kimmel, A. R. (1987) *Methods Enzymol.* 152:507).

20 For example, stringent salt concentration will ordinarily be less than about 750 mM NaCl and 75 mM trisodium citrate, preferably less than about 500 mM NaCl and 50 mM trisodium citrate, and more preferably less than about 250 mM NaCl and 25 mM trisodium citrate. Low stringency hybridization can be obtained in the absence of organic solvent, e.g., formamide, while high stringency hybridization can be obtained in the presence of at least
25 about 35% formamide, and more preferably at least about 50% formamide. Stringent temperature conditions will ordinarily include temperatures of at least about 30° C, more preferably of at least about 37° C, and most preferably of at least about 42° C. Varying additional parameters, such as hybridization time, the concentration of detergent, e.g., sodium dodecyl sulfate (SDS), and the inclusion or exclusion of carrier DNA, are well known to
30 those skilled in the art. Various levels of stringency are accomplished by combining these various conditions as needed. In a preferred embodiment, hybridization will occur at 30° C in 750 mM NaCl, 75 mM trisodium citrate, and 1% SDS. In a more preferred embodiment, hybridization will occur at 37° C in 500 mM NaCl, 50 mM trisodium citrate, 1% SDS, 35% formamide, and 100 µg/ml denatured salmon sperm DNA (ssDNA). In a most preferred

embodiment, hybridization will occur at 42° C in 250 mM NaCl, 25 mM trisodium citrate, 1% SDS, 50% formamide, and 200 µg/ml ssDNA. Useful variations on these conditions will be readily apparent to those skilled in the art.

For most applications, washing steps that follow hybridization will also vary in stringency. Wash stringency conditions can be defined by salt concentration and by temperature. As above, wash stringency can be increased by decreasing salt concentration or by increasing temperature. For example, stringent salt concentration for the wash steps will preferably be less than about 30 mM NaCl and 3 mM trisodium citrate, and most preferably less than about 15 mM NaCl and 1.5 mM trisodium citrate. Stringent temperature conditions for the wash steps will ordinarily include a temperature of at least about 25° C, more preferably of at least about 42° C, and even more preferably of at least about 68° C. In a preferred embodiment, wash steps will occur at 25° C in 30 mM NaCl, 3 mM trisodium citrate, and 0.1% SDS. In a more preferred embodiment, wash steps will occur at 42 C in 15 mM NaCl, 1.5 mM trisodium citrate, and 0.1% SDS. In a more preferred embodiment, wash steps will occur at 68° C in 15 mM NaCl, 1.5 mM trisodium citrate, and 0.1% SDS. Additional variations on these conditions will be readily apparent to those skilled in the art. Hybridization techniques are well known to those skilled in the art and are described, for example, in Benton and Davis (Science 196:180, 1977); Grunstein and Hogness (Proc. Natl. Acad. Sci., USA 72:3961, 1975); Ausubel et al. (Current Protocols in Molecular Biology, Wiley Interscience, New York, 2001); Berger and Kimmel (Guide to Molecular Cloning Techniques, 1987, Academic Press, New York); and Sambrook et al., Molecular Cloning: A Laboratory Manual, Cold Spring Harbor Laboratory Press, New York.

By "substantially identical" is meant a polypeptide or nucleic acid molecule exhibiting at least 50% identity to a reference amino acid sequence (for example, any one of the amino acid sequences described herein) or nucleic acid sequence (for example, any one of the nucleic acid sequences described herein). Preferably, such a sequence is at least 60%, more preferably 80% or 85%, and more preferably 90%, 95% or even 99% identical at the amino acid level or nucleic acid to the sequence used for comparison.

Sequence identity is typically measured using sequence analysis software (for example, Sequence Analysis Software Package of the Genetics Computer Group, University of Wisconsin Biotechnology Center, 1710 University Avenue, Madison, Wis. 53705, BLAST, BESTFIT, GAP, or PILEUP/PRETTYBOX programs). Such software matches identical or similar sequences by assigning degrees of homology to various substitutions, deletions, and/or other modifications. Conservative substitutions typically include

substitutions within the following groups: glycine, alanine; valine, isoleucine, leucine; aspartic acid, glutamic acid, asparagine, glutamine; serine, threonine; lysine, arginine; and phenylalanine, tyrosine. In an exemplary approach to determining the degree of identity, a BLAST program may be used, with a probability score between e^{-3} and e^{-100} indicating a closely related sequence.

By "structural polyprotein" is meant a composite amino acid molecule comprising at least two separable polypeptides that contribute to a viral capsid or envelope. In one embodiment, the polypeptides are susceptible to cleavage with a viral enzyme (e.g., capsid autoprotease and signalases).

An exemplary structural polyprotein sequence is provided at Genbank Accession No. ABX40006.1, which is reproduced below.

```
MEFIPTQTFYNRRYQPRPWTPTPTIQVIRPRPRPQRQAGQLAQL
ISAVNKLTMRAVPQQKPRNRNKNKKQKQKQAPQNNNTNQKKQPPKKKPAQKKKKPGRR
ERMCMKIENDCIFEVKHEGKVTGYACLVGDKVMKPAHVKGITDNADLAKLAFKRSSKY
DLECAQIPVHMKSDASKFTHEKPEGYYNWHHGAQVYSGGRFTIPTGAGKPGDSGRPIF
DNKGRVVAIVLGGANEGARTALSVVTWNKDITVKITPEGAEWLSLAI PVMCLLANTTF
PCSQPPCTPCCYEKEPEETLRMLEDNVMRPGYYQLLQASLTCSPHRQRRSTKDNFNVY
KATRPYLAHCPDCGEGHSCSPVALERIRNEATDGTLLKIQVSLQIGIKTDDSHDWTCL
RYMDNHMPADAERAGLFVRTSAPCTITGTMGHFI LARCPKGETLTVGFTDSRKISHSC
THPFHHDPPVIGREKFHSRPHGKELPCSTYVQSTAATTEEIEVHMPPDTPDRTLMSQ
QSGNVKITVNGQTVRYKCNCGGSNEGLTTTDKVINNCKVDQCHAAVTNHKKWQYNSPL
VPRNAELGDRGKIHI PFPLANVTCRVPKARNPTVTYGNQVIMLLYPDHPTLLSYRN
MGEEPNYQEEWVMHKKKEVVLTVPTGLEVTWGNNEPYKYWPQLSTNGTAHGHPHEIIL
YYYELYPTMTVVVSVATFILLSMVGMAAGMCMCARRRCITPYELTPGATVPFLLSLI
CCIRTAKAATYQEAAILWLNEQQPLFWLQALI PLAALIVLCNCLRLLPCCCKTLAFLA
VMSVGAHTVSAYEHVTVI PNTVGVYPYKTLVNRPGYSPMVLEMELLSVTLEPTLSLDYI
TCEYKTVIPSPYVKCCGTAECKDKNLDPYCKVFTGVYPFMWGGAYCFDAENTQLSE
AHVEKSECKTEFASAYRAHTASASAKLRVLYQGNNITVTAYANGDHAHTVVKDAKFIV
GPMSSAWTPFDNKIVVYKGDVYNMDYPFGAGRPGQFGDIQSRTPESKDVYANTQLVL
QRPVAGTVHVPYSQAPSGFKYWLKERGASLQHTAPFGCQIATNPVRAVNCAVGNMPS
IDIPEAAFTRVVDAPSLTDMSCVPACTHSSDFGGVAIIKYAASKKGKCAVHSMTNAV
TIREAEIEVEGNSQLQISFSTALASAEFRVQVCSTQVHCAAECPPKDHIVNYPASHT
TLGVQDISATAMSWVQKITGGVGLVVAALILIVLVCVSFSRH"
```

An exemplary expression vector encoding the structural polyprotein shown above is provided at Genbank Accession No. EU224268 (Figure 24).

A second exemplary structural polyprotein sequence is provided at Genbank Accession No. ABX40011.1", which is reproduced below:

```
MEFIPTQTFYNRRYQPRPWAPRPTIQVIRPRPRPQRQAGQLAQL
ISAVNKLTMRAVPQQKPRNRNKNKKQKQKQAPQNDPKQKKQPPQKKPAQKKKKPGRR
ERMCMKIENDCIFEVKHEGKVMGYACLVGDKVMKPAHVKGITDNADLAKLAFKRSSKY
DLECAQIPVHMKSDASKFTHEKPEGYYNWHHGAQVYSGGRFTIPTGAGKPGDSGRPIF
DNKGRVVAIVLGGANEGARTALSVVTWNKDITVKITPEGAEWLSLALPVLCLLANTTF
PCSQPPCTPCCYEKEPEETLRMLEDNVMRPGYYQLLQASLTCSPHRQRRSTKDNFNVY
KATRPYLAHCPDCGEGHSCSPVALERIRNEATDGTLLKIQVSLQIGIKTDDSHDWTCL
RYMDSHTPADAERAGLLVRTSAPCTITGTMGHFI LARCPKGETLTVGFTDSRKISHSC
THPFHHEPPVIGRERFHSRPHGKELPCSTYVQSTAATAEEIEVHMPPDTPDRTLMTQ
QSGNVKITVNGQTVRYKCNCGGSNEGLTTTDKVINNCKIDQCHAAVTNHKNWQYNSPL
```

VPRNAELGDRKGKIHIIPFPLANVTCRVPKARNPTVTYGKNQVTMLLYPDHPTLLSYRN
 MGQEPNYHEEWVTHKKEVTLTVPTGLEVTWGNNEPYKYWPQMSTNGTAHGHPHEIIL
 YYYELYPTMTVVIIVSVASFVLLSMVGTAVGMCVCARRRCITPYELTPGATVPFLLSLL
 CCVRTTKAATYYEAAAYLWNEQQPLFWLQALIPLAALIVLCNCLKLLPCCCKTLAFLA
 5 VMSIGAHTVSAYEHVTVIPNTVGVVPYKTLVNRPGYSPMVLEMELQSVTLEPTLSLDYI
 TCEYKTVIPSPYVKCCGTAECKDKSLPDYSCKVFTGVYPFMWGGAYCFCDAENTQLSE
 AHVEKSECKTEFASAYRAHTASASAKLRVLYQGNNITVAAYANGDHAVTVKDAKFVV
 GPMSSAWTPFDNKIVVYKGDVYNMDYPPFGAGRPGQFGDIQSRTPESKDVYANTQLVL
 10 QRPAAAGTVHVPYSQAPSGFKYWLKERGASLQHTAPFGCQIATNPVRAVNCAVGNIPIIS
 IDIPDAAFTRVVDAPSVTDMSCVEPACTHSSDFGGVAIIKYTASKKGKCAVHSMTNAV
 TIREADVEVEGNSQLQISFSTALASAEFRVQVCSTQVHCAAACHPPKDHIVNYPASHT
 TLGVQDISTTAMSWVQKITGGVGLIVAVAALILIVLVCVSFSRH

By "subject" is meant a mammal, including, but not limited to, a human or non-human mammal, such as a bovine, equine, canine, ovine, or feline.

15 Ranges provided herein are understood to be shorthand for all of the values within the range. For example, a range of 1 to 50 is understood to include any number, combination of numbers, or sub-range from the group consisting 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, or 50.

20 As used herein, the terms "treat," "treating," "treatment," and the like refer to reducing or ameliorating a disorder and/or symptoms associated therewith. It will be appreciated that, although not precluded, treating a disorder or condition does not require that the disorder, condition or symptoms associated therewith be completely eliminated.

As used herein, the term "vaccine" refers to a formulation which contains VLPs or
 25 DNAs, or other gene-based vaccine vectors, of the present invention, which is in a form that is capable of being administered to a vertebrate and which induces a protective immune response sufficient to induce immunity to prevent and/or ameliorate an infection and/or to reduce at least one symptom of an infection and/or to enhance the efficacy of another dose of VLPs or DNA vaccines. Typically, the vaccine comprises a conventional saline or buffered
 30 aqueous solution medium in which the composition of the present invention is suspended or dissolved. In this form, the composition of the present invention can be used conveniently to prevent, ameliorate, or otherwise treat an infection. Upon introduction into a host, the vaccine is able to provoke an immune response including, but not limited to, the production of antibodies and/or cytokines and/or the activation of cytotoxic T cells, antigen presenting
 35 cells, helper T cells, dendritic cells and/or other cellular responses. In certain embodiments, a vaccine can also be a protein. For example, recombinant proteins have been produced by genetically engineering cells to produce one or more foreign genes, which in turn produce proteins that serve as the immunogen.

As used herein, the term "virus-like particle" (VLP) refers to a structure that in at least one attribute resembles a virus but which has not been demonstrated to be infectious. Virus-like particles in accordance with the invention do not carry genetic information encoding for the proteins of the virus-like particles. In general, virus-like particles lack a viral genome and, therefore, are noninfectious. In addition, virus-like particles can often be produced in large quantities by heterologous expression and can be easily purified.

Unless specifically stated or obvious from context, as used herein, the term "or" is understood to be inclusive. Unless specifically stated or obvious from context, as used herein, the terms "a", "an", and "the" are understood to be singular or plural.

Unless specifically stated or obvious from context, as used herein, the term "about" is understood as within a range of normal tolerance in the art, for example within 2 standard deviations of the mean. About can be understood as within 10%, 9%, 8%, 7%, 6%, 5%, 4%, 3%, 2%, 1%, 0.5%, 0.1%, 0.05%, or 0.01% of the stated value. Unless otherwise clear from context, all numerical values provided herein are modified by the term about.

The recitation of a listing of chemical groups in any definition of a variable herein includes definitions of that variable as any single group or combination of listed groups. The recitation of an embodiment for a variable or aspect herein includes that embodiment as any single embodiment or in combination with any other embodiments or portions thereof.

Any compositions or methods provided herein can be combined with one or more of any of the other compositions and methods provided herein.

BRIEF DESCRIPTION OF THE DRAWINGS

Figures 1A-1D show the characterization of CHIKV E pseudotyped lentiviral vectors. Figure 1A is a schematic representation of the CHIKV genome and CHIKV E expression vector used for incorporation of CHIKV E from strains 37997 and LR2006 OPY-1 into pseudotyped lentiviral vectors. The CHIKV genome consists of nonstructural polyproteins NS1, NS2, NS3 and NS4 and structural polyproteins capsid (C) and envelope (E: E3, E2, 6K and E1) (top). The polypeptide E genes from strains 37997 and LR2006 OPY-1 were inserted into an expression vector (bottom). Figure 1B includes two graphs. The graph on the left shows the infectivity of the indicated pseudotyped lentiviral vectors in several CHIKV-permissive cell lines, including 293A human renal epithelial, HeLa cervical epithelial, Vero renal epithelial, A549 squamous epithelial and baby hamster kidney (BHK) cells. The pseudotyped vectors were standardized by HIV-1 Gag p24 (left) or the indicated concentration of p24 and used to infect 293A cells (right). After

incubation with pseudotyped vectors for 24 hours, cells were lysed and luciferase activity was measured. The experiment was performed in triplicate. Figure 1C includes two graphs that show the pH-dependent entry of CHIKV pseudotyped lentiviral vectors.

Pseudotyped lentiviral vectors were incubated in the presence of the indicated amounts of ammonium chloride (left) and chloroquine (right). The experiment was performed in triplicate. Data are presented as the percentage of activity at the indicated dose relative to activity with no treatment. Figure 1D is a graph showing neutralization measured with pseudotyped lentiviral vectors in sera from mice injected with CHIKV (strain S-27). Sera were incubated at the indicated dilutions with VSV-G, CHIKV strain 37997 or LR2006 OPY-1 E-pseudotyped lentiviral vectors and the mixture infected to 293A cells. Luciferase activity was analyzed 24 hours after infection. The experiment was performed in triplicate. No inhibition was observed with control non-immune antisera.

Figures 2A-2C show the schematic representation of plasmid expression vectors and characterization of CHIKV VLPs. Figure 2A provides a schematic representation of CHIKV C-E or E expression vectors used for DNA vaccine and VLP production. The CHIKV structural polyproteins capsid plus envelope (C-E) or E alone from strains 37997 and LR2006 OPY-1 were inserted into an expression vector. 293T cells were transfected with each of the indicated plasmids. Expression was measured 48 h after transfection by Western blotting as described previously (29) with antisera reactive with CHIKV. Figure 2B includes a graph, Western blot, and electron micrograph. VLPs were purified from the supernatants of 293F cells transfected with C-E expression vector (C-E37997) (left). The supernatants were harvested 72 hours after transfection followed by OptiPrep density gradient centrifugation. Each fraction was characterized for its buoyant density (left upper panel) and protein content (left lower panel) by Western blot analysis with antisera to CHIKV. The fractionated VLPs were observed by transmission electron microscopy with magnification 20,000x (left, bar 100 nm) (right). Figure 2C provides a comparison of cryo-EM reconstructions of CHIKV VLP with Sindbis virus showing that CHIKV VLP is structurally similar to alphaviruses. Shaded-surface representation of the 3D density map of CHIKV VLP (left upper panel) and Sindbis virus (right upper panel) viewed along an icosahedral 2-fold axis. The white triangle marks the boundary of an icosahedral asymmetric unit. The numbers show the positions of the icosahedral 2-, 3-, and 5-fold axes limiting an asymmetric unit. The central cross-section through the cryo-EM maps of CHIKV VLP (left lower panel) and Sindbis virus (right lower panel). The orientations

of the icosahedral (2-, 3-, and 5-fold) axes as well as the quasi-threefold (q3) axis are shown with white lines. Maps are calculated to 1.8 Å resolution.

Figures 3A-3D are graphs showing the neutralization of CHIKV strains 37997 and LR2006 OPY-1 after DNA or VLP vaccination in mice and monkeys. Sera from immunized mice 10 days after the final immunization were tested with CHIKV strain 37997 (Figure 3A) or LR2006 OPY-1 (Figure 3B) E pseudotyped lentiviral vectors. Mice were immunized with the indicated DNA or $v_{LP37997}$. Each C-E or E (strain 37997 and LR2006 OPY-1, respectively) plasmid was injected at 0, 3 and 6 weeks. $v_{LP37997}$ with or without Ribi adjuvant was injected at 2 and 6 weeks. The experiment was performed in triplicate. The symbols show the average of the five mice and bars show the standard error of the mean. The curve fit was calculated by Prism software. Figure 3C shows results from monkeys immunized with $v_{LP37997}$ or PBS (control) at 0, 4, and 24 weeks. A neutralizing assay was performed with CHIKV strain 37997 (left panel) or LR2006 OPY-1 (right panel) E pseudotyped lentiviral vectors in sera collected from immunized monkeys at 10 days after each immunization. The symbols show the average of the six monkeys and bars show the standard error of the mean. Figure 3D shows the neutralizing activity against CHIKV LR2006 OPY-1 in immunized monkeys' sera after the 2nd and 3rd immunizations was confirmed by a standard plaque reduction neutralization test (PRNT). The symbols show the average of the six monkeys and bars show the standard error of the mean.

Figures 4A-4D are graphs showing protection against CHIKV LR2006 OPY-1 challenge in monkeys immunized with VLPs and in a CHIKV mouse model after passive transfer of purified IgG. Figure 4A quantitates results obtained in monkeys injected with PBS (Control) or immunized with $v_{LP37997}$. Monkeys were challenged with 10^{10} PFU of the CHIKV strain LR2006 OPY-1 15 weeks after the final boost. The peak viremia at 24 hours after challenge was measured by plaque assay. The serum dilutions started from 1:200 (limit of detection = 1000 PFU/ml). Error bars represent the standard error of the mean. Figure 4B is a graph showing the percentage of monocytes in the monkeys' white blood cells. Monocyte percentage was measured using a hematology analyzer before and 7 days after challenge with CHIKV. Error bars represent the standard error of the mean. A non-parametric two *t*-test was used for statistical analysis (Control vs. VLPs at 7 days, $P = 0.0036$; Control at 0 days vs. 7 days, $P = 0.0015$; VLPs at 0 days vs. 7 days, $P > 0.5$). Figure 4C shows the number of viral RNA copies present following passive transfer of purified IgG from a monkey immunized with VLPs (Immune) or a control monkey (Control IgG) into mice (2 mg of total IgG per mouse,

n=5 per group). Recipient mice were challenged 24 hours after IgG transfer with a lethal LR2006 OPY-1 challenge (30 PFU) by intradermal injection. The viremia in the mice after challenge was measured by quantitative RT-PCR (limit of detection = 40 RNA copies/ml). Error bars represent the standard error of the mean. Figure 4D shows a survival curve of mice passively transferred with control IgG or CHIKV immunized IgG against lethal LR2006 OPY-1 challenge.

Figure 5 shows the characterization of CHIKV E pseudotyped lentiviral vectors by buoyant density sedimentation and Western blot analysis. Plasmids encoding the indicated CHIKV Env strains were cotransfected with lentiviral expression vectors into 293T cells. Forty-eight hours after transfection, supernatants were harvested and run on sedimentation gradients as described previously. Quantification of gradient fractions is shown with the indicated strains, showing colocalization of Env with the Gag fraction of the expected buoyant density for lentiviral particles (1.08-1.1 g/ml) (upper panel). Western blot analysis of gradient fractions for CHIKV E1 /E2 and Gag are shown (lower panel).

Figure 6 shows the CMV/R-CHIKV C-E3-E2-6K-E1 plasmid (Strain 37997).

Figure 7A shows the sequence of the insert (SEQ ID NO:1). Figure 7B shows the sequence of the entire plasmid sequence (SEQ ID NO: 2).

Figure 8A shows the CMV/R-CHIKV C-E3-E2-6K-E1 plasmid (Strain OPY1).

Figure 8B shows the sequence of the insert (SEQ ID NO:3) . Figure 8C shows the entire plasmid sequence (SEQ ID NO: 4).

Figure 9A shows the CMV/R-Middleburg virus VLP plasmid. Figure 9B shows the entire plasmid sequence (SEQ ID NO: 5).

Figure 10A shows the CMV/R-Sleeping disease virus VLP plasmid. Figure 10B shows the entire plasmid sequence (SEQ ID NO: 6).

Figure 11 (A and B). Panel A shows the CMV/R-Getah virus VLP plasmid. Panel B shows the entire plasmid sequence (SEQ ID NO: 7).

Figure 12A shows the CMV/R-Venezuelan equine encephalitis virus VLP plasmid. Figure 12B shows the entire plasmid sequence (SEQ ID NO: 8).

Figure 13A shows the CMV/R-Western equine encephalitis virus VLP plasmid. Figure 13B shows the entire plasmid sequence (SEQ ID NO: 9).

Figure 14A shows the CMV/R-Eastern equine encephalitis virus VLP plasmid. Figure 14B shows the entire plasmid sequence (SEQ ID NO: 10).

Figure 15A shows the CMV/R-Sindbis virus VLP plasmid. Figure 15B shows the entire plasmid sequence (SEQ ID NO: 11).

Figure 16A shows the CMV/R-Semliki forest virus VLP plasmid. Figure 16B shows the entire plasmid sequence (SEQ ID NO: 12).

5 Figure 17A shows the CMV/R-Salmon pancreas disease virus VLP plasmid. Figure 17B shows the entire plasmid sequence (SEQ ID NO: 13).

Figure 18A shows the CMV/R-Ross River virus VLP plasmid. Figure 18B shows the entire plasmid sequence (SEQ ID NO: 14).

10 Figure 19A shows the CMV/R-O'nyong-nyong virus VLP plasmid. Figure 19B shows the entire plasmid sequence (SEQ ID NO: 15).

Figure 20A shows the CMV/R-Mayaro virus VLP plasmid. Figure 20B shows the entire plasmid sequence (SEQ ID NO: 16).

Figure 21A shows the CMV/R-Barmah Forest virus VLP plasmid. Figure 21B shows the entire plasmid sequence (SEQ ID NO: 17).

15 Figure 22A shows the CMV/R-Aura virus VLP plasmid. Figure 22B shows the entire plasmid sequence (SEQ ID NO: 18).

Figure 23A shows the CMV/R-CHIKV E3-E2-6K-E1 plasmid (Strain 37997) and the sequence of the insert without the capsid (C) (SEQ ID NO:19). Figure 23B shows the CMV/R-CHIKV E3-E2-6K-E1 plasmid (Strain OPY1) and the sequence of the insert without
20 the capsid (C) (SEQ ID NO: 20).

Figure 24 shows the sequence of Genbank Accession No. EU224268, which is a Cloning vector pCHIKV-LR ic, complete sequence. See, Tsetsarkin,K., Higgs,S., McGee,C.E., De Lamballerie,X.,Charrel,R.N. and Vanlandingham,D.L. Infectious clones of Chikungunya virus (La Reunion isolate) for vector competence studies, Vector Borne
25 Zoonotic Dis. 6 (4), 325-337 (2006).

Figure 25 shows the sequence of Genbank Accession No. EU224270, which is the complete sequence of the Cloning vector pCHIK-37997ic.

DETAILED DESCRIPTION OF THE INVENTION

30 Chikungunya virus (CHIKV) has infected millions of people in Africa, Europe, and Asia since its re-emergence in Kenya in 2004. The evolution and spread of the virus into new geographic areas, and the severity of the disease, present a serious public health threat in the absence of a vaccines or anti-viral therapies. The invention provides compositions and

methods for inducing protective immunity. The invention is based, at least in part, on the discovery that a recombinant virus-like particle (VLP) vaccine protects against CHIKV infection in non-human primates. VLPs were generated by expression of viral structural proteins. These had similar buoyant density and morphology to replication-competent virus.

5 Immunization with VLPs elicited neutralizing antibodies against homologous and heterologous envelope. Monkeys immunized with VLPs produced high titer cross-reactive neutralizing antibodies that protected against high dose challenge with emerging epidemic CHIKV. Furthermore, passive transfer of these antibodies from immune monkeys protected against lethal CHIKV challenge in immunodeficient mice, demonstrating that protection is mediated by the
10 humoral immune response. Immunization with the VLP vaccine is a strategy that would prevent the infection and spread of CHIKV and related pathogenic viruses in humans.

Accordingly, the invention provides immunogenic compositions containing one or more alphavirus (e.g., Chikungunya virus) structural polypeptides. In particular, the immunogenic composition (e.g., vaccine) contains envelope or capsid polypeptides sufficient to
15 form a virus-like particle. The invention further provides nucleic acid molecules encoding alphavirus (Chikungunya) structural polypeptides, expression vectors comprising these coding sequences, and methods of using these nucleic acid molecules for the preparation of virus-like particles. In other embodiments, the invention provides DNA vaccines that provide for the expression of one or more viral polypeptides in the cell of a subject.

20

Immunogenic Compositions

The invention provides compositions and methods for inducing an immunological response in a subject, particularly a human, which involves inoculating the subject with a VLP comprising one or more alphavirus or CHIKV polypeptides, or fragments thereof, in a
25 suitable carrier for the purpose of inducing or enhancing an immune response. In one embodiment, an immune response protects the subject from a CHIKV infection, or inflammatory consequences thereof (e.g., arthritis). The administration of this immunological composition may be used either therapeutically in subjects already experiencing a CHIKV infection, or may be used prophylactically to prevent a CHIKV
30 infection.

In certain embodiments, CHIKV candidate vaccines were developed by comparing the immunogenicity of gene products derived from two disparate strains, the 37997 strain from West Africa and the latest outbreak strain, OPY-1, of the East/Central/South African genotype, to develop CHIKV candidate vaccines. These strains share ~95% amino acid

sequence similarity but have distinct biological differences, particularly related to their host range.

VLPs of the invention are useful for preparing vaccines and immunogenic compositions. One important feature of VLPs is the ability to express surface proteins so that the immune system of a vertebrate induces an immune response against said protein. However, not all proteins can be expressed on the surface of VLPs. There may be many reasons why certain proteins are not expressed, or be poorly expressed, on the surface of VLPs. One reason is that said protein is not directed to the membrane of a host cell or that said protein does not have a transmembrane domain.

The preparation of immunogenic compositions and vaccines is known to one skilled in the art. The vaccine includes a VLP comprising one or more CHIKV polypeptides, or fragments thereof. The invention also provides expression vectors encoding one or more CHIKV polypeptides or fragments thereof or variants thereof. Such an immunogenic composition is delivered *in vivo* in order to induce or enhance an immunological response in a subject, such as a humoral response.

For example, a VLP comprising one or more CHIKV polypeptides, or fragments or variants thereof are delivered *in vivo* in order to induce an immune response.

Typically vaccines are prepared in an injectable form, either as a liquid solution or as a suspension. Solid forms suitable for injection may also be prepared as emulsions, or with the polypeptides encapsulated in liposomes. Vaccine antigens are usually combined with a pharmaceutically acceptable carrier, which includes any carrier that does not induce the production of antibodies harmful to the subject receiving the carrier. Suitable carriers typically comprise large macromolecules that are slowly metabolized, such as proteins, polysaccharides, polylactic acids, polyglycolic acids, polymeric amino acids, amino acid copolymers, lipid aggregates, and inactive virus particles. Such carriers are well known to those skilled in the art. These carriers may also function as adjuvants.

The VLP comprising one or more CHIKV polypeptides, or fragments or variants thereof may be administered in combination with an adjuvant (e.g., Ribi). Adjuvants are immunostimulating agents that enhance vaccine effectiveness. If desired, the VLP comprising one or more CHIKV polypeptides or fragments or variants thereof are administered in combination with an adjuvant that enhances the effectiveness of the immune response generated against the antigen of interest. Effective adjuvants include, but are not limited to, aluminum salts such as aluminum hydroxide and aluminum phosphate, muramyl

peptides, bacterial cell wall components, saponin adjuvants, and other substances that act as immunostimulating agents to enhance the effectiveness of the composition.

Immunogenic compositions, i.e. the VLP comprising one or more CHIKV polypeptides, pharmaceutically acceptable carrier and adjuvant, also typically contain diluents, such as water, saline, glycerol, ethanol. Auxiliary substances may also be present, such as wetting or emulsifying agents, pH buffering substances, and the like. Proteins may be formulated into the vaccine as neutral or salt forms. The immunogenic compositions are typically administered parenterally, by injection; such injection may be either subcutaneously or intramuscularly. Additional formulations are suitable for other forms of administration, such as by suppository or orally. Oral compositions may be administered as a solution, suspension, tablet, pill, capsule, or sustained release formulation.

Immunogenic compositions are administered in a manner compatible with the dose formulation. The immunogenic composition comprises an immunologically effective amount of the VLP and other previously mentioned components. By an immunologically effective amount is meant a single dose, or a composition administered in a multiple dose schedule, that is effective for the treatment or prevention of an infection. The dose administered will vary, depending on the subject to be treated, the subject's health and physical condition, the capacity of the subject's immune system to produce antibodies, the degree of protection desired, and other relevant factors. Precise amounts of the active ingredient required will depend on the judgement of the practitioner, but typically range between 5 μ g to 250 μ g of antigen per dose.

The invention provides a VLP for use in treating or preventing an alphavirus infection (e.g., Chikungunya infection).

Polypeptide Expression

In general, VLPs comprising one or more CHIKV polypeptides of the invention may be produced by transformation of a suitable host cell with all or part of a polypeptide-encoding nucleic acid molecule or fragment thereof in a suitable expression vehicle.

Those skilled in the field of molecular biology will understand that any of a wide variety of expression systems may be used to provide the recombinant protein. The precise host cell used is not critical to the invention. A polypeptide of the invention may be produced in a prokaryotic host (e.g., *E. coli*) or in a eukaryotic host (e.g., *Saccharomyces cerevisiae*, insect cells, e.g., Sf21 cells, or mammalian cells, e.g., NIH 3T3, HeLa, COS cells). Such cells are available from a wide range of sources (e.g., the American Type Culture Collection,

Rockland, Md.; also, see, e.g., Ausubel et al., supra). Non limiting examples of insect cells are, *Spodoptera frugiperda* (Sf) cells, e.g. Sf9, Sf21, *Trichoplusia ni* cells, e.g. High Five cells, and *Drosophila* S2 cells. Examples of fungi (including yeast) host cells are *S.*

cerevisiae, *Kluyveromyces lactis* (*K lactis*), species of *Candida* including *C. albicans* and *C.*

5 *glabrata*, *Aspergillus nidulans*, *Schizosaccharomyces pombe* (*S. pombe*), *Pichia pastoris*, and *Yarrowia lipolytica*. Examples of mammalian cells are COS cells, baby hamster kidney cells, mouse L cells, LNCaP cells, Chinese hamster ovary (CHO) cells, human embryonic kidney (HEK) cells, African green monkey cells, CV1 cells, HeLa cells, MDCK cells, Vero and Hep-2 cells. *Xenopus laevis* oocytes, or other cells of amphibian origin, may also be used.

10 Prokaryotic host cells include bacterial cells, for example, *E. coli*, *B. subtilis*, and mycobacteria.

Methods of cloning said proteins are known in the art. For example, the gene encoding a specific CHIKV or any alphavirus protein can be isolated by RT-PCR from polyadenylated mRNA extracted from cells which had been infected with said virus. The
15 resulting product gene can be cloned as a DNA insert into a vector. The term "vector" refers to the means by which a nucleic acid can be propagated and/or transferred between organisms, cells, or cellular components. Vectors include plasmids, viruses, bacteriophages, pro-viruses, phagemids, transposons, artificial chromosomes, and the like, that replicate autonomously or can integrate into a chromosome of a host cell. A vector can also be a naked
20 RNA polynucleotide, a naked DNA polynucleotide, a polynucleotide composed of both DNA and RNA within the same strand, a poly-lysine-conjugated DNA or RNA, a peptide-conjugated DNA or RNA, a liposome-conjugated DNA, or the like, that is not autonomously replicating. In many, but not all, common embodiments, the vectors of the present invention are plasmids or bacmids.

25 The invention further provides nucleotides that encode proteins, including chimeric molecules, cloned into an expression vector that can be expressed in a cell that provides for the formation of VLPs. An "expression vector" is a vector, such as a plasmid, that is capable of promoting expression, as well as replication of a nucleic acid incorporated therein. Typically, the nucleic acid molecule to be expressed is "operably linked" to a promoter and/or
30 enhancer, and is subject to transcription regulatory control by the promoter and/or enhancer. In one embodiment, the VLP comprises one or more alphavirus envelope proteins, and in particular CHIKV virus envelope proteins. In another embodiment, the one or more envelope proteins are any one or more of E3, E2, 6K and E1. In another embodiment, the VLP further comprises a CHIKV virus capsid protein. In related embodiments, the Chikungunya virus

capsid protein is used. In still another embodiment, the VLPs are comprised of capsid, E3, E2, 6K and E1. In another embodiment, the expression vector is a mammalian expression vector or baculovirus vector.

The method of transformation or transfection and the choice of expression vehicle will depend on the host system selected. Transformation and transfection methods are described, e.g., in Ausubel et al. (supra); expression vehicles may be chosen from those provided, e.g., in Cloning Vectors: A Laboratory Manual (P. H. Pouwels et al., 1985, Supp. 1987).

A variety of expression systems exist for the production of the polypeptides of the invention. Expression vectors useful for producing such polypeptides include, without limitation, chromosomal, episomal, and virus-derived vectors, e.g., vectors derived from bacterial plasmids, from bacteriophage, from transposons, from yeast episomes, from insertion elements, from yeast chromosomal elements, from viruses such as baculoviruses, papova viruses, such as SV40, vaccinia viruses, adenoviruses, fowl pox viruses, pseudorabies viruses and retroviruses, and vectors derived from combinations thereof.

Constructs and/or vectors provided herein comprise CHIKV polynucleotides that encode structural polypeptides, including envelope proteins or capsid proteins or portions thereof as described herein. The vector may be, for example, a phage, plasmid, viral, or retroviral vector. The constructs and/or vectors that comprise the nucleotides should be operatively linked to an appropriate promoter, such as the CMV promoter, phage lambda PL promoter, the *E. coli* lac, phoA and tac promoters, the SV40 early and late promoters, and promoters of retroviral LTRs are non-limiting examples. Other suitable promoters will be known to the skilled artisan depending on the host cell and/or the rate of expression desired. The expression constructs will further contain sites for transcription initiation, termination, and, in the transcribed region, a ribosome-binding site for translation. The coding portion of the transcripts expressed by the constructs will preferably include a translation initiating codon at the beginning and a termination codon appropriately positioned at the end of the polypeptide to be translated.

Expression vectors will preferably include at least one selectable marker. Such markers include dihydrofolate reductase, G418 or neomycin resistance for eukaryotic cell culture and tetracycline, kanamycin or ampicillin resistance genes for culturing in *E. coli* and other bacteria. Among vectors preferred are virus vectors, such as baculovirus, poxvirus (e.g., vaccinia virus, avipox virus, canarypox virus, fowlpox virus, raccoonpox virus, swinepox virus, etc.), adenovirus (e.g., canine adenovirus), herpesvirus, and retrovirus. Other

vectors that can be used with the invention comprise vectors for use in bacteria, which comprise pQE70, pQE60 and pQE-9, pBluescript vectors, Phagescript vectors, pNH8A, pNH16a, pNH18A, pNH46A, ptrc99a, pKK223-3, pKK233-3, pDR540, pRIT5. Among preferred eukaryotic vectors are pFastBac1 pWINEO, pSV2CAT, pOG44, pXT1 and pSG, pSVK3, pBPV, pMSG, and pSVL. Other suitable vectors will be readily apparent to the skilled artisan.

Recombinant constructs can be prepared and used to transfect, infect, or transform and can express viral proteins, including those described herein, into eukaryotic cells and/or prokaryotic cells. Thus, the invention provides for host cells which comprise a vector (or vectors) that contain nucleic acids which code for CHIKV structural genes, including capsid, E3, E2, 6K, and E1 or portions thereof, and/or any chimeric molecule described above, and permit the expression of CHIKV structural genes, including capsid E3, E2, 6K, and E1, or portions thereof, and/or any chimeric molecule described above in said host cell under conditions which allow the formation of VLPs.

In one embodiment, said vector is a recombinant baculovirus. In another embodiment, said recombinant baculovirus is transfected into an insect cell. In a preferred embodiment, said cell is an insect cell. In another embodiment, said insect cell is a Sf9 cell.

In another embodiment, said vector and/or host cell comprise nucleotides that encode CHIKV genes, including capsid, E3, E2, 6K, and E1, or portions thereof as described herein. In another embodiment, said vector and/or host cell consists essentially of CHIKV capsid E3, E2, 6K, and E1, or portions thereof as described herein. In a further embodiment, said vector and/or host cell consists of CHIKV protein comprising capsid, E3, E2, 6K, and E1, or portions thereof, as described herein. These vector and/or host cell contain CHIKV core E3, E2, 6K, and E1, or portions thereof, as described herein, and may contain additional cellular constituents such as cellular proteins, baculovirus proteins, lipids, carbohydrates etc.

One particular bacterial expression system for polypeptide production is the *E. coli* pET expression system (Novagen, Inc., Madison, Wis). According to this expression system, DNA encoding a polypeptide is inserted into a pET vector in an orientation designed to allow expression. Since the gene encoding such a polypeptide is under the control of the T7 regulatory signals, expression of the polypeptide is achieved by inducing the expression of T7 RNA polymerase in the host cell. This is typically achieved using host strains that express T7 RNA polymerase in response to IPTG induction. Once produced, a recombinant polypeptide is then isolated according to standard methods known in the art, for example, those described herein.

Another bacterial expression system for polypeptide production is the pGEX expression system (Pharmacia). This system employs a GST gene fusion system that is designed for high-level expression of genes or gene fragments as fusion proteins with rapid purification and recovery of functional gene products. The protein of interest is fused to the carboxyl terminus of the glutathione S-transferase protein from *Schistosoma japonicum* and is readily purified from bacterial lysates by affinity chromatography using Glutathione Sepharose 4B. Fusion proteins can be recovered under mild conditions by elution with glutathione. Cleavage of the glutathione S-transferase domain from the fusion protein is facilitated by the presence of recognition sites for site-specific proteases upstream of this domain. For example, proteins expressed in pGEX-2T plasmids may be cleaved with thrombin; those expressed in pGEX-3X may be cleaved with factor Xa.

Once a recombinant polypeptide of the invention is expressed, it is isolated, e.g., using affinity chromatography. In one example, an antibody (e.g., produced as described herein) raised against a polypeptide of the invention may be attached to a column and used to isolate the recombinant polypeptide. Lysis and fractionation of polypeptide-harboring cells prior to affinity chromatography may be performed by standard methods (see, e.g., Ausubel et al., supra).

Once isolated, the recombinant protein can, if desired, be further purified, e.g., by high performance liquid chromatography (see, e.g., Fisher, Laboratory Techniques In Biochemistry and Molecular Biology, eds., Work and Burdon, Elsevier, 1980). Polypeptides of the invention, particularly short peptide fragments, can also be produced by chemical synthesis (e.g., by the methods described in Solid Phase Peptide Synthesis, 2nd ed., 1984 The Pierce Chemical Co., Rockford, Ill.). These general techniques of polypeptide expression and purification can also be used to produce and isolate useful peptide fragments or analogs (described herein).

CHIKV polypeptides and Analogs

The invention provides VLPs comprising one or more CHIKV polypeptides. Also included in the invention are VLPs comprising one or more CHIKV polypeptides or fragments thereof that are modified in ways that enhance or do not inhibit their ability to modulate an immune response. In one embodiment, the invention provides methods for optimizing a CHIKV amino acid sequence or nucleic acid sequence by producing an alteration. Such alterations may include certain mutations, deletions, insertions, or post-translational modifications. The invention further includes analogs of any naturally-

occurring polypeptide of the invention. Analogs can differ from the naturally-occurring the polypeptide of the invention by amino acid sequence differences, by post-translational modifications, or by both. Analogs of the invention will generally exhibit at least 85%, more preferably 90%, and most preferably 95% or even 99% identity with all or part of a naturally-
5 occurring amino, acid sequence of the invention. The length of sequence comparison is at least 10, 13, 15 amino acid residues, preferably at least 25 amino acid residues, and more preferably more than 35 amino acid residues.

Alterations of a alphavirus or CHIKV polypeptide include but are not limited to site-directed, random point mutagenesis, homologous recombination (DNA shuffling),
10 mutagenesis using uracil containing templates, oligonucleotide-directed mutagenesis, phosphorothioate-modified DNA mutagenesis, mutagenesis using gapped duplex DNA or the like. Additional suitable methods include point mismatch repair, mutagenesis using repair-deficient host strains, restriction-selection and restriction-purification, deletion mutagenesis, mutagenesis by total gene synthesis, double-strand break repair, and the like. Mutagenesis,
15 e.g., involving chimeric constructs, is also included in the present invention. In one embodiment, mutagenesis can be guided by known information of the naturally occurring molecule or altered or mutated naturally occurring molecule, e.g., sequence, sequence comparisons, physical properties, crystal structure or the like.

In one embodiment, the invention provides polypeptide variants that differ from a
20 reference polypeptide. The term "variant" refers to an amino acid sequence that is altered by one or more amino acids with respect to a reference sequence. The variant can have "conservative" changes, wherein a substituted amino acid has similar structural or chemical properties, e.g., replacement of leucine with isoleucine. Alternatively, a variant can have "nonconservative" changes, e.g., replacement of a glycine with a tryptophan. Analogous
25 minor variations can also include amino acid deletion or insertion, or both. Guidance in determining which amino acid residues can be substituted, inserted, or deleted without eliminating biological or immunological activity can be found using computer programs well known in the art, for example, DNASTAR software. Desirably, variants show substantial biological activity. In one embodiment, a protein variant forms a VLP and elicits an antibody
30 response when administered to a subject.

Natural variants can occur due to mutations in the proteins. These mutations may lead to antigenic variability within individual groups of infectious agents, for example CHIKV. Thus, a person infected with a particular strain develops antibody against that virus, as newer virus strains appear, the antibodies against the older strains no longer recognize the

newer virus and reinfection can occur. The invention encompasses all antigenic and genetic variability of proteins from infectious agents for making VLPs.

Again, in an exemplary approach to determining the degree of identity, a BLAST program may be used, with a probability score between e^{-3} and e^{-100} indicating a closely related sequence. Modifications include *in vivo* and *in vitro* chemical derivatization of polypeptides, e.g., acetylation, carboxylation, phosphorylation, or glycosylation; such modifications may occur during polypeptide synthesis or processing or following treatment with isolated modifying enzymes. Analogs can also differ from the naturally-occurring polypeptides of the invention by alterations in primary sequence. These include genetic variants, both natural and induced (for example, resulting from random mutagenesis by irradiation or exposure to ethanemethylsulfate or by site-specific mutagenesis as described in Sambrook, Fritsch and Maniatis, *Molecular Cloning: A Laboratory Manual* (2d ed.), CSH Press, 1989, or Ausubel et al., *supra*). Also included are cyclized peptides, molecules, and analogs which contain residues other than L-amino acids, e.g., D-amino acids or non-naturally occurring or synthetic amino acids, e.g., .beta. or .gamma. amino acids.

In addition to full-length polypeptides, the invention also includes fragments of any one of the polypeptides of the invention. As used herein, the term "a fragment" means at least 5, 10, 13, or 15. In other embodiments a fragment is at least 20 contiguous amino acids, at least 30 contiguous amino acids, or at least 50 contiguous amino acids, and in other embodiments at least 60 to 80 or more contiguous amino acids. Fragments of the invention can be generated by methods known to those skilled in the art or may result from normal protein processing (e.g., removal of amino acids from the nascent polypeptide that are not required for biological activity or removal of amino acids by alternative mRNA splicing or alternative protein processing events).

Non-protein analogs having a chemical structure designed to mimic CHIKV VLPs or one or more CHIKV polypeptides functional activity can be administered according to methods of the invention. CHIKV analogs may exceed the physiological activity of native CHIKV. Methods of analog design are well known in the art, and synthesis of analogs can be carried out according to such methods by modifying the chemical structures such that the resultant analogs exhibit the immunomodulatory activity of a native CHIKV polypeptide. These chemical modifications include, but are not limited to, substituting alternative R groups and varying the degree of saturation at specific carbon atoms of the native CHIKV molecule. Preferably, the analogs are relatively resistant to *in vivo* degradation, resulting in a more

prolonged therapeutic effect upon administration. Assays for measuring functional activity include, but are not limited to, those described in the Examples below.

CHIKV Polynucleotides

5 In general, the invention includes any nucleic acid sequence encoding a VLP comprising one or more CHIKV polypeptides or a fragment thereof, where the fragment induces an immune response. An isolated nucleic acid molecule is can be manipulated by recombinant DNA techniques well known in the art. Thus, a nucleotide sequence contained in a vector in which 5' and 3' restriction sites are known, or for which polymerase chain
10 reaction (PCR) primer sequences have been disclosed, is considered isolated, but a nucleic acid sequence existing in its native state in its natural host is not. In certain exemplary embodiments, the vector comprises Chikungunya₃₇₉₉₇ or Chikungunya_{OPY-1} nucleic acid segments, or fragments thereof. The vector may further comprise a CMV/R promoter. The vector may also comprise the capsid protein, or a fragment thereof.

15 In other exemplary embodiments, the vector comprises an envelope protein selected from the group consisting of E3, E2, 6K, and E1. In certain examples, the vaccine may comprise capsid, E3, E2, 6K and E1. In other examples, the vaccine may comprise E3, E2, 6K and E1.

According to certain preferred embodiments of the invention, C-Env₃₇₉₉₇ is set forth
20 as SEQ ID NO:1; Env₃₇₉₉₇ is set forth as SEQ ID NO:19; C-Env_{OPY-1} is set forth as SEQ ID NO:3; Env_{OPY-1} is set forth as SEQ ID NO: 20.

Shown below is the nucleotide sequence corresponding to the capsid (SEQ ID NO: 21) and E3, E2, 6K and E1 (SEQ ID NO: 19) of the CMV/R-CHIKV C-E3-E2-6K-E1 plasmid (Strain 37997). The CMV/R expression vector is described, for example, in US
25 Patent no. 7,094,598, which is incorporated herein in its entirety.

E3-E2-6K-E1

SEQ ID NO: 19

Atgagcctcgcctcccgtcttgctgttggtgcaaacactacattccctgctctcagccgccttgacaccctgctgctacgaaaaggaaccgg
aaagcaccttgccgatgcttgaggacaacgtgatgagaccggatactaccagctactaaaagcatcgctgacttgctctcccaccgccaaagac
30 gcagtactaaggacaatttaattgtctataaagccacaagaccatatctagctcattgtcctgactcgggagaaggccattcgtccacagccctatc
gcattggagcgcacagaaatgaagcaacggacggaacgctgaaaatccaggtctcttgcatcgggataaagacagatgacagccacgattg
gaccaagctgcgctatatggatagccatacggcagcggagcggagcggagcggattgctgtaaggacttcagcaccgtgcacgatcaccggg
accatgggacactttattctcgccgatgccgaaaggagagacgctgacagtgggatttacggacagcagaagatcagccacacatgcacaca
cccgttccatcatgaaccacgtgataggtaggagaggttccactctgaccacaacatggtaaagagttaccttgacgcacgtacgtgcagag
35 caccgctgccactgctgaggagatagaggtgcatatgccccagatactcctgaccgcacgctgatgacgcagcagcttggaacgtgaagatca
cagtaatgggcagacggtgcggtacaagtgaactgcggtggctcaaacgagggactgacaaccacagacaaagtgatcaataactgcaaaatt
gatcagtgccatgctgcagtcactaatcacaagaattggcaatacaactcccctttagtcccgcgaacgctgaactcggggaccgtaaaggaag

atccacatcccattcccattggcaaacgtgactgcagagtgcacaaagcaagaaccctacagtaacttacggaaaaaccaagtaccatgctg
 ctgtatcctgacctccgacactctgtctaccgtaacatgggacaggaaccaaattaccacgaggagtggtgacacacaagaaggaggttacct
 tgacctgctactgagggtctggaggtcactggggcaacaacgaaccatacaagtactggccgcagatgtctacgaacgggtactgctcatggtc
 accacatgagataatctgtactattatgagctgtaccccactatgactgtagtcaattgtgtcgggtggcctcgttcgttctgtcgtatggtgggcaca
 5 gcaagtgggaatgtgtgtgtgcgcacggcgagatgcattacacatatgaattaacaccaggagccactgttcccttcctgctcagcctgctatgctg
 cgtcagaacgaccaaggcgccacatattacgaggctcgggcatactatggaacgaacagcagcccctgttctggttgaggctcttatcccgct
 ggccgccttgatcgtcctgtgcaactgtctgaaactcttgccatgctgctgtaagaccctggcttttttagccgtaatgagcatcgggtgccacactgtg
 agcgcgtacgaacacgtaacagtgtatcccgaacacgggtgggagtaccgtataagactctgtcaacagaccgggttacagccccatggtgttggg
 gatggagctacaatcagtcaccttggaccaacactgtcacttgactacatcacgtgcgagtacaaaactgtatccccctcccgtacgtgaagtgt
 10 gtggtacagcagagtgaaggacaagagcctaccagactacagctgcaaggtcttactggaggtctaccattatgtggggcggcgccctactgctt
 ttgcgacgccgaaaatacgaattgagcgaggcacatgtagagaaatctgaatcttgcaaacagagtttgcatcggcctacagagcccacaccg
 catcggcgtcggcgaaagctccgctcttaccaggaacaacattaccgtagctgcctacgctaacgggtgacctgccgtcacagtaaggac
 gccaaagtttgcgtgggcccattgtcctccgctggacacctttgacaacaaaatcgtggtgtacaaaggcgacgtctacaacatggactaccac
 cttttggcgaggaagaccaggacaattgtgacattcaagtcgtacaccggaagtaagacgtttatgccaacactcagttggtactacagag
 15 gccagcagcaggcaggtacatgtaccatactcagggcacctctggttcaagtattggtgaaggaacgaggagcatcgtacagcacacgg
 caccgttcggttgccagattgcgacaaacccggtgaagagctgtaaattgcgctgtggggaacataccaatttccatgcacataccggatcgggcctt
 tactaggggtgtcgtatgcaccctctgtaacggacatgtcatgcgaagtaccagcctgcactcactcctccgactttgggggctcgccatcatcaaat
 acacagctagcaagaaggttaaatgtgcagtacattcgtatgaccaacggcgttaccattcgagaagccgacgtagaagttaggggaactccca
 gctgcaaatatccttctcaacagccctggcaagcgccgagtttcgctgcaagtgtgtccacacaagtacactgcgcagccgcatgccaccctcc
 20 aaaggaccacatagtcattaccagcatcacacaccaccttgggggtccaggatataccacaacggcaatgtcttgggtgcagaagattacggg
 aggagtaggattaattgttctgttgccttaattttaattgtggtgctatgcgtgtcgttttagcaggcac

Core

SEQ ID NO: 21

25 Atggagttcatcccagcgaacactttctataacagaaggtaccaacccccgacctggggccccacgccctacaattcaagtaattagacctagacca
 cgtccacagaggcaggtctgggcaactcggccagctgatctccgagtcacaaatgacatgcgcgcggttacctcaacagaagcctcgcagaa
 atcggaaaaacaagaagcaaaaggcagaagaagcaggcgccgcaaaacgacccaaagcaaaagaagcaaccaccacaaaagaagccggctc
 aaaagaagaagaaccaggccgtaggagagaatgtcatgaaaattgaaaatgattgcatttcgaagtcaagcatgaaggcaaatgatggg
 ctacgcatgcctgggtgggggataaagtaataaaccagcacatgtgaagggaactatcgacaatgccgatctggctaaactggcctttaagcggtc
 30 gtctaatacagatcttgaatgtgcacagataccgggtgcacatgaagtctgatgcctcgaagtttaccacgagaaacccgaggggtactataactgg
 catcagggagcagtcagattacaggaggccggttactatcccaggggtgcaggcaagccgggagacagcggcagaccgatcttcgacaac
 aaaggacgggtggtggccatcgtcctaggaggggccaacgaaggtgccgcacggccctctcgtggtgacgtggaacaaagacatcgtcaca
 aaaattacccctgagggagccgaagagtgg

35 Shown below is the nucleotide sequence corresponding to the capsid (SEQ ID NO:
 22) and E3, E2, 6K and E1 (SEQ ID NO: 20) of the CMV/R-CHIKV C-E3-E2-6K-E1
 plasmid (Strain OPY-1).

E3-E2-6K-E1

SEQ ID NO: 20

40 Atgagtttccatcccagttatgtgctgttggcaaacaccacgttccctgtcccagccccctgcacgccctgctgctacgaaaaggaaccgg
 aggaaacctacgcatgcttgaggacaacgtcatgagacctgggtactatcagctgctacaagcatccttaacatgttctccccaccggcagcgcac
 gcagcacaaggacaacttcaatgtctataaagccacaagaccatacttagctcactgtcccagctgtggagaagggcactcgtgccatagtcagg
 tagcactagaacgcatcagaatgaagcgacagacgggacgctgaaaatccaggtctccttgcaaatcggaataaagacggatgacagccacga
 45 ttggaccaagctgcgttatatggacaaccacatgccagcagacgcagagaggcggggctatttgaagaacatcagcaccgtgtacgattactgg

aacaatgggacacttcatcctggccgatgtccaaaaggggaaactctgacggtgggattcactgacagtaggaagattagtcactcatgtacgca
 cccatttcaccacgacctcctgtgataggtcgggaaaaattccattcccagccgagcagcaggttaagagctacctgacgacgtacgtgcagag
 caccgccgaactaccgaggagatagaggtacacatgccccagacacctctgacgcacattaatgtcacaacagtcgggcaacgtaaagatc
 acagtcaatggccagacggtgcggtacaagtgttaattgcggtggctcaaatgaaggactaacaactacagacaaagtattataactgcaaggtt
 5 gatcaatgtcatgcccgggtcaccaatcacaaaaagtggcagtataactccccctggtcccgctaagtgtgaactggggaccgaaaaggaaaa
 attcacatcccgtttccgctggcaaatgtaacatgcagggtgcctaaagcaaggaaacccaccgtgacgtacgggaaaaaccaagtcacatgcta
 ctgtatcctgaccaccaactcctgtcctaccggaatatgggagaagaaccaaactatcaagaagagtggtgatgcataagaaggagtcgtg
 ctaaccgtgccgactgaagggtcgaggtcacgtggggcaacaacgagccgtataagattggccgagttatctacaaacgggtacagcccatgg
 ccaccgcatgagataattctgtattattatgagctgtacccactatgactgtagtagttgtgtcagtgccacgttcatactcctgtcgtggtgggta
 10 tggcagcggggatgtgcatgtgtgcacgacgcagatgcacacccgtatgaactgacaccaggagctaccgtcccttctcgttagcctaataatg
 ctgcatcagaacagctaaagcggccacataccaagagggtgcgatatacctgtggaacgagcagcaaccttgttttggtacaaagccctattccg
 ctggcagccctgattgtctatgcaactgtctgagactcttaccatgctgctgtaaacgttggctttttagccgtaatgagcgtcgggtgccacactgt
 gagcgcgtacgaacacgtaacagtgatcccgaacacgggtgggagtagcgtataagactctagtcaatagacctggctacagccccatggtattgg
 agatggaactactgtcagtcacttggagccaactatcgcttgattacatcacgtgcgagtacaaaacggctacccgtctccgtacgtgaagtgtc
 15 gcggtacagcagagtgaaggacaaaaacctaactgactacagctgaagggtcttcaccggcgtctacccatttatgtggggcggcgccctactgctt
 ctgagcagctgaaaacacgcagttgagcgaagcacacgtgggagaagtccgaatcatgaaaacagaatttgcatcagcatacaggggtcataccg
 catctgcatcagctaagctccgcgtcctttaccaaggaaataacatcactgtaactgcctatgcaaacggcgacatgccgtcacagttaaggacgc
 caaattcattgtggggccaatgtcttcagcctggacaccttgcacaacaaaattgtggtgtacaaaggtgacgtctataacatggactaccggccctt
 tggcgaggaagaccaggacaatttggcgatatccaaagtcgcacacctgagagtaagacgtctatgtaatacacaactggtagtcagagac
 20 cggctgtgggtacgttacacgtgccatactctcaggcaccatctggctttaagtattggtaaaaagaacgcggggcgtcgtgcagcacacagcac
 catttggctgccaatagcaacaaacccggtgaagagcgggtgaactgcgcgtagggaacatgccatctccatcgacataccggaagcggccttc
 actagggtcgtgcagcgcctcttaacggacatgtcgtgcgaggtaccagcctgcaccattctcagacttggggggtcgtccattattaata
 tgcagccagcaagaaggaaggtgtgcggtgcattcgatgactaacgccgtcactattcggaagctgagatagaagttgaagggaattctcagct
 gcaaatctcttctgcagggccttagccagcgcgaattccgctacaagtctgtctacacaagtacactgtgcagccgagtgccacccccgaag
 25 gaccacatagtcaactaccggcgctacataccacctcggggtccaggacatctccgtacggcgatgtcatgggtgcagaagatcacgggag
 ggtggtggactgggtgtgtgtgcccgcactgattctaactgtggtgctatgcgtgtcgttcagcaggcac

Core

SEQ ID NO: 22

Atggagttcatcccaacccaaactttttacaataggaggtaccagcctcgacctggactccgcgcctactatccaagtcacaggcc
 30 cagaccgcgcctcagaggcaagctgggcaacttcccagctgatctcagcagttataaactgacaatgcgcgcggtaccacaac
 agaagccacgcaggaatcggaagaataagaagcaaaaacacagcgccacaaaacacacaaatcaaaagaagcag
 ccacctaaaaagaaaccggctcaaaagaaaaagaagccggggccgagagagaggatgtgcatgaaaatcgaaaatgattgtattttc
 gaagtcaagcacgaaggttaaggtaacaggttacgcgtgccttgggtgggggacaaaagtaataaaccagcacacgtaaaggggacca
 tcgataacgcggacctggccaaactggcctttaagcgggtcatctaagtatgaccttgaatgcgcgcagatacccggtgcatgaagtcc
 35 gacgcttcgaagttacccatgagaaaccggaggggtactacaactggcaccacggagcagtagtactcaggaggccggttcac
 catccctacaggtgtggaacaccaggggacagcggcagaccgatcttcgacaacaagggacgcgtggtggccatagtcttaggag
 gagctaataagggagcccgtacagccctctcggtggtgacctggaataaagacattgtcactaaaatcacccccgagggggccgaa
 gattgg

In a particular embodiment, a nucleic acid molecule set forth as SEQ ID NO: 1, 19, 3
 40 or 20 includes a nucleotide sequence encoding a polypeptide having at least about 50%, 60%,
 70%, 75%, 80%, 81%, 82%, 83%, 84%, 85%, 86%, 87%, 88%, 89%, 90%, 91%, 92%, 93%,
 94%, 95%, 96%, 97%, 98%, or more identity (e.g., when compared to the overall length of
 the amino acid sequence) to a polypeptide encoding an envelope protein selected from capsid,
 E3, E2, 6K and E1 or E3, E2, 6K and E1.

In some embodiments of the invention proteins may comprise mutations containing alterations which produce silent substitutions, additions, or deletions, but do not alter the properties or activities of the encoded protein or how the proteins are made. Nucleotide variants can be produced for a variety of reasons, e.g., to optimize codon expression for a particular host See U.S. patent publication 2005/0118191, herein incorporated by reference in its entirety for all purposes.

In addition, the nucleotides can be sequenced to ensure that the correct coding regions were cloned and do not contain any unwanted mutations. The nucleotides can be subcloned into an expression vector (e.g. baculovirus) for expression in any cell. A person with skill in the art understands that various subcloning methods are available and are possible.

An isolated nucleic acid may be substantially purified, but need not be. For example, a nucleic acid that is isolated within a cloning or expression vector is not pure in that it may comprise only a tiny percentage of the material in the cell in which it resides. Such a nucleic acid is isolated, as the term is used herein, because it is readily manipulatable by standard techniques known to those of ordinary skill in the art.

CHIKV VLP Production

The invention also provides constructs and methods for producing a VLP comprising CHIKV polypeptides, or fragments thereof, as well as compositions and methods that increase the efficiency of VLP production. For example, the addition of leader sequences to the CHIKV capsid, E3, E2, 6K, and E1 or portions thereof, that can improve the efficiency of protein transporting within the cell. In another example, a heterologous signal sequence can be fused to the CHIKV capsid, E3, E2, 6K, and E1 or portions thereof. In one embodiment, the signal sequence can be derived from the gene of an insect cell. Another method to increase efficiency of VLP production is to codon optimize the nucleotides that encode CHIKV capsid, E3, E2, 6K, and E1 or portions thereof, for a specific cell type.

Methods of cloning said proteins are known in the art. For example, the gene encoding a specific CHIKV or any alphavirus protein can be isolated by RT-PCR from polyadenylated mRNA extracted from cells which had been infected with said virus. The resulting gene can be cloned as a DNA insert into a vector. The term "vector" refers to the means by which a nucleic acid can be propagated and/or transferred between organisms, cells, or cellular components. Vectors include plasmids, viruses, bacteriophages, pro-viruses, phagemids, transposons, artificial chromosomes, and the like, that replicate autonomously or can integrate into a chromosome of a host cell. A vector can also be a naked RNA

polynucleotide, a naked DNA polynucleotide, a polynucleotide composed of both DNA and RNA within the same strand, a poly-lysine-conjugated DNA or RNA, a peptide-conjugated DNA or RNA, a liposome-conjugated DNA, or the like, that is not autonomously replicating. In many, but not all, common embodiments, the vectors of the present invention are plasmids or bacmids.

Thus, the invention comprises nucleotides that encode proteins, including chimeric molecules, cloned into an expression vector that can be expressed in a cell that induces the formation of VLPs of the invention. An "expression vector" is a vector, such as a plasmid that is capable of promoting expression, as well as replication of a nucleic acid incorporated therein. Typically, the nucleic acid to be expressed is "operably linked" to a promoter and/or enhancer, and is subject to transcription regulatory control by the promoter and/or enhancer. In one embodiment, the VLP comprises one or more alphavirus envelope proteins, and in particular CHIKV virus envelope proteins. In another embodiment, the one or more envelope proteins are selected from the group consisting of E3, E2, 6K and E1. In another embodiment, the VLP comprises a CHIKV virus capsid protein. In related embodiments, the Chikungunya virus capsid protein is used. In another embodiment, the VLPs are comprised of E3, E2, 6K and E1. In still another embodiment, the VLPs are comprised of capsid, E3, E2, 6K and E1. In another embodiment, the expression vector is a baculovirus vector.

The invention also provides methods of producing a VLP comprising CHIKV polypeptides, or fragments thereof. In one example, the method involves expressing in a cell a polynucleotide encoding a CHIKV polypeptide and culturing said cell, thereby producing VLPs. In one embodiment, a cell (e.g., human cell) is infected with a DNA vaccine, where the DNA vaccine is a DNA vector, comprising a nucleic acid segment encoding an alphavirus capsid protein or one or more alphavirus envelope proteins, or fragments thereof to produce an alphavirus VLP. In particular, the alphavirus is CHIKV.

Depending on the expression system and host cell selected, the VLPs are produced by growing host cells transformed by an expression vector under conditions whereby the recombinant proteins are expressed and VLPs are formed. In one embodiment, the invention comprises a method of producing a VLP, that involves transfecting vectors encoding at least one alphavirus protein into a suitable host cell and expressing said alphavirus protein under conditions that allow VLP formation. In another embodiment, the eukaryotic cell is selected from the group consisting of, yeast, insect, amphibian, avian or mammalian cells. The selection of the appropriate growth conditions is within the skill or a person with skill of one of ordinary skill in the art.

Methods to grow cells that produce VLPs of the invention include, but are not limited to, batch, batch-fed, continuous and perfusion cell culture techniques. In one embodiment, a cell comprising a CHIKV or alphavirus polynucleotide is grown in a bioreactor or fermentation chamber where cells propagate and express protein (e.g. recombinant proteins) for purification and isolation. Typically, cell culture is performed under sterile, controlled temperature and atmospheric conditions. A bioreactor is a chamber used to culture cells in which environmental conditions such as temperature, atmosphere, agitation and/or pH can be monitored. In one embodiment, the bioreactor is a stainless steel chamber. In another embodiment, said bioreactor is a pre-sterilized plastic bag (e.g. Cellbag.RTM., Wave Biotech, Bridgewater, N.J.). In other embodiment, said pre-sterilized plastic bags are about 50 L to 1000 L bags.

The VLPs are isolated using methods that preserve the integrity thereof, such as by gradient centrifugation, e.g., cesium chloride, sucrose and iodixanol, as well as standard purification techniques including, e.g., ion exchange and gel filtration chromatography.

The following is an example of how VLPs of the invention can be made, isolated and purified. A person of skill in the art appreciates that there are additional methods that can be used to make and purify VLPs. Accordingly, the invention is not limited to the methods described herein.

In general, production of VLPs of the invention is accomplished by seeding a mammalian cell (e.g., human embryonic kidney (293T) cells) or Sf9 cells (non-infected) into shaker flasks, allowing the cells to expand and scaling up as the cells grow and multiply (for example from a 125-ml flask to a 50 L Wave bag). The medium used to grow the cells is formulated for the appropriate cell line (preferably serum free media, e.g. insect medium ExCell-420, JRH). Next, the cells are transfected or infected with an appropriate vector (e.g., mammalian expression vector or for SF(cells recombinant baculovirus at the most efficient multiplicity of infection (e.g. from about 1 to about 3 plaque forming units per cell). The polynucleotides, or portions thereof, are expressed in the cells where they self assemble into VLPs and are secreted from the cells approximately 24 to 72 hours post infection. Usually, transfection or infection is most efficient when the cells are in mid-log phase of growth (4×10^6 cells/ml) and are at least about 90% viable.

VLPs of the invention are harvested approximately 48 to 120 hours post infection, when the levels of VLPs in the cell culture medium are near the maximum but before extensive cell lysis. The cell density and viability at the time of harvest can be about 0.5×10^6 cells/ml to about 1.5×10^6 cells/ml with at least 20% viability, as shown by dye exclusion

assay. Next, the medium is removed and clarified. NaCl can be added to the medium to a concentration of about 0.4 to about 1.0 M, preferably to about 0.5 M, to avoid VLP aggregation. The removal of cell and cellular debris from the cell culture medium containing VLPs of the invention can be accomplished by tangential flow filtration (TFF) with a single
5 use, pre-sterilized hollow fiber 0.5 or 1.00 μm filter cartridge or a similar device.

Next, VLPs in the clarified culture medium are concentrated by ultrafiltration using a disposable, pre-sterilized 500,000 molecular weight cut off hollow fiber cartridge. The concentrated VLPs can be diafiltered against 10 volumes pH 7.0 to 8.0 phosphate-buffered saline (PBS) containing 0.5 M NaCl to remove residual medium components.

10 The concentrated, diafiltered VLPs can be further purified on a 20% to 60% discontinuous sucrose gradient in pH 7.2 PBS buffer with 0.5 M NaCl by centrifugation at 6,500 x g for 18 hours at about 4 C to about 10 C. Usually VLPs will form a distinctive visible band between about 30% to about 40% sucrose or at the interface (in a 20% and 60% step gradient) that can be collected from the gradient and stored. This product can be diluted
15 to comprise 200 mM of NaCl in preparation for the next step in the purification process. This product contains VLPs and may contain intact baculovirus particles.

Further purification of VLPs can be achieved by anion exchange chromatography, or 44% isopycnic sucrose cushion centrifugation. In anion exchange chromatography, the sample from the sucrose gradient (see above) is loaded into column containing a medium
20 with an anion (e.g. Matrix Fractogel EMD TMAE) and eluted via a salt gradient (from about 0.2 M to about 1.0 M of NaCl) that can separate the VLP from other contaminants (e.g. baculovirus and DNA/RNA). In the sucrose cushion method, the sample comprising the VLPs is added to a 44% sucrose cushion and centrifuged for about 18 hours at 30,000 g. VLPs form a band at the top of 44% sucrose, while baculovirus precipitates at the bottom and
25 other contaminating proteins stay in the 0% sucrose layer at the top. The VLP peak or band is collected.

The intact baculovirus can be inactivated, if desired. Inactivation can be accomplished by chemical methods, for example, formalin or .beta.-propiolactone (BPL). Removal and/or inactivation of intact baculovirus can also be largely accomplished by using
30 selective precipitation and chromatographic methods known in the art, as exemplified above. Methods of inactivation comprise incubating the sample containing the VLPs in 0.2% of BPL for 3 hours at about 25 C to about 27 C. The baculovirus can also be inactivated by incubating the sample containing the VLPs at 0.05% BPL at 4 C for 3 days, then at 37 C for one hour.

After the inactivation/removal step, the product comprising VLPs can be run through another diafiltration step to remove any reagent from the inactivation step and/or any residual sucrose, and to place the VLPs into the desired buffer (e.g. PBS). The solution comprising VLPs can be sterilized by methods known in the art (e.g. sterile filtration) and stored in the refrigerator or freezer.

The above techniques can be practiced across a variety of scales. For example, T-flasks, shake-flasks, spinner bottles, up to industrial sized bioreactors. The bioreactors can comprise either a stainless steel tank or a pre-sterilized plastic bag (for example, the system sold by Wave Biotech, Bridgewater, N.J.). A person with skill in the art will know what is most desirable for their purposes.

In certain embodiments, a DNA vaccine or VLP comprises agents, such as nucleic acid molecules, siRNA, microRNA, chemotherapeutic agents, imaging agents, and/or other agents that need to be delivered to a patient.

Accordingly, the present invention provides methods of treating viral diseases and/or disorders or symptoms thereof which comprise administering a therapeutically effective amount of a pharmaceutical composition comprising a VLP or DNA of the formulae herein to a subject (e.g., a mammal such as a human). Thus, one embodiment is a method of treating a subject suffering from or susceptible to a viral infection, viral disease or disorder or symptom thereof. The method includes the step of administering to the mammal a therapeutic or prophylactic amount of an amount of a compound herein sufficient to treat the disease or disorder or symptom thereof, under conditions such that the disease or disorder is prevented or treated.

The methods herein include administering to the subject (including a subject identified as in need of such treatment) an effective amount of a compound described herein, or a composition described herein to produce such effect. Identifying a subject in need of such treatment can be in the judgment of a subject or a health care professional and can be subjective (e.g. opinion) or objective (e.g. measurable by a test or diagnostic method).

As used herein, the terms “treat,” “treating,” “treatment,” and the like refer to reducing or ameliorating a disorder and/or symptoms associated therewith. It will be appreciated that, although not precluded, treating a disorder or condition does not require that the disorder, condition or symptoms associated therewith be completely eliminated.

As used herein, the terms “prevent,” “preventing,” “prevention,” “prophylactic treatment” and the like refer to reducing the probability of developing a disorder or condition

in a subject, who does not have, but is at risk of or susceptible to developing a disorder or condition.

The therapeutic methods of the invention (which include prophylactic treatment) in general comprise administration of a therapeutically effective amount of the agents herein, such as a VLP or DNA of a formulae herein to a subject (e.g., animal, human) in need thereof, including a mammal, particularly a human. Such treatment will be suitably administered to subjects, particularly humans, suffering from, having, susceptible to, or at risk for a disease, disorder, or symptom thereof. Determination of those subjects "at risk" can be made by any objective or subjective determination by a diagnostic test or opinion of a subject or health care provider (e.g., genetic test, enzyme or protein marker, Marker (as defined herein), family history, and the like). The agents herein may be also used in the treatment of any other disorders in which an alphavirus may be implicated.

In one embodiment, the invention provides a method of monitoring treatment progress. The method includes the step of determining a level of diagnostic marker (Marker) (e.g., any target delineated herein modulated by a compound herein, a protein or indicator thereof, etc.) or diagnostic measurement (e.g., screen, assay) in a subject suffering from or susceptible to a disorder or symptoms thereof associated with an alphavirus, in which the subject has been administered a therapeutic amount of a compound herein sufficient to treat the disease or symptoms thereof. The level of Marker determined in the method can be compared to known levels of Marker in either healthy normal controls or in other afflicted patients to establish the subject's disease status. In preferred embodiments, a second level of Marker in the subject is determined at a time point later than the determination of the first level, and the two levels are compared to monitor the course of disease or the efficacy of the therapy. In certain preferred embodiments, a pre-treatment level of Marker in the subject is determined prior to beginning treatment according to this invention; this pre-treatment level of Marker can then be compared to the level of Marker in the subject after the treatment commences, to determine the efficacy of the treatment.

PHARMACEUTICAL COMPOSITIONS AND ADMINISTRATION

The invention features pharmaceutical compositions that comprise VLPs of an alphavirus as described herein. The pharmaceutical compositions useful herein contain a pharmaceutically acceptable carrier, including any suitable diluent or excipient, which includes any pharmaceutical agent that does not itself induce the production of an immune response harmful to the vertebrate receiving the composition, and which may be administered

without undue toxicity and a VLP of the invention. As used herein, the term "pharmaceutically acceptable" means being approved by a regulatory agency of the Federal or a state government or listed in the U.S. Pharmacopia, European Pharmacopia or other generally recognized pharmacopia for use in mammals, and more particularly in humans.

5 These compositions can be useful as a vaccine and/or antigenic compositions for inducing a protective immune response in a vertebrate.

In particular embodiments, the invention encompasses an antigenic formulation comprising VLPs which comprises at least one viral protein, for example one alphavirus protein. The alphavirus may be selected from the group consisting of, but not limited to,
10 Chikungunya virus, Sindbis virus, Eastern equine encephalitis (EEE) virus, Western equine encephalitis (WEE) virus, and Venezuelan equine encephalitis (VEE) virus.

In certain preferred embodiments, the pharmaceutical composition comprises VLPs of Chikungunya virus, and a pharmaceutically acceptable carrier. In other certain preferred embodiments, the pharmaceutical composition comprises VLPs of Chikungunya virus, an
15 adjuvant, and a pharmaceutically acceptable carrier.

In one embodiment, the VLPs are comprised of Chikungunya virus envelope proteins, for example, the envelope proteins can be selected from the group consisting of E3, E2, 6K and E1. In another embodiment, the pharmaceutical composition further comprises a Chikungunya virus capsid protein. The Chikungunya virus capsid protein is, in certain
20 examples, a capsid protein. In certain examples, the VLPs are comprised of E3, E2, 6K and E1. In other examples, the VLPs are comprised of capsid, E3, E2, 6K and E1.

The invention also encompasses a vaccine formulation comprising VLPs that comprise at least one viral protein, for example one alphavirus protein. The alphavirus may be selected from the group consisting of, but not limited to, Chikungunya virus, Sindbis virus,
25 Eastern equine encephalitis (EEE) virus, Western equine encephalitis (WEE) virus, and Venezuelan equine encephalitis (VEE) virus.

In certain preferred embodiments, the vaccine composition comprises VLPs of Chikungunya virus, and a pharmaceutically acceptable carrier. In other certain preferred embodiments, the vaccine composition comprises VLPs of Chikungunya virus, an adjuvant,
30 and a pharmaceutically acceptable carrier. In one embodiment, the vaccine composition comprises VLPs of Chikungunya virus envelope proteins, for example, the envelope proteins can be selected from the group consisting of E3, E2, 6K and E1. In another embodiment, the vaccine composition further comprises a Chikungunya virus capsid protein and a pharmaceutically acceptable carrier or excipient. The Chikungunya virus capsid protein is, in

certain examples, a capsid protein. In certain examples, the VLPs are comprised of E3, E2, 6K and E1. In other examples, the VLPs are comprised of capsid, E3, E2, 6K and E1.

Pharmaceutically acceptable carriers include but are not limited to saline, buffered saline, dextrose, water, glycerol, sterile isotonic aqueous buffer, and combinations thereof. A
5 thorough discussion of pharmaceutically acceptable carriers, diluents, and other excipients is presented in Remington's Pharmaceutical Sciences (Mack Pub. Co. N.J. current edition). The formulation should suit the mode of administration. In a preferred embodiment, the formulation is suitable for administration to humans, preferably is sterile, non-particulate and/or non-pyrogenic.

10 The composition, if desired, can also contain minor amounts of wetting or emulsifying agents, or pH buffering agents. The composition can be a solid form, such as a lyophilized powder suitable for reconstitution, a liquid solution, suspension, emulsion, tablet, pill, capsule, sustained release formulation, or powder. Oral formulation can include standard carriers such as pharmaceutical grades of mannitol, lactose, starch, magnesium stearate,
15 sodium saccharine, cellulose, magnesium carbonate, etc.

In certain embodiments, the VLP composition is supplied in liquid form, for example in a sealed container indicating the quantity and concentration of the VLP composition. Preferably, the liquid form of the VLP composition is supplied in a hermetically sealed container at least about 50 µg/ml, more preferably at least about 100 µg/ml, at least about 200
20 µg/ml, at least 500 µg/ml, or at least 1 mg/ml.

Generally, VLPs or DNA vaccines of the invention are administered in an effective amount or quantity (as described herein) sufficient to stimulate an immune response against one or more strains of a virus as described here, for example an alphavirus, e.g. CHIKV. Preferably, administration of the VLP of the invention elicits immunity against a virus, for
25 example an alphavirus, in particular example CHIKV. Typically, the dose can be adjusted within this range based on, e.g., age, physical condition, body weight, sex, diet, time of administration, and other clinical factors. The prophylactic vaccine formulation is systemically administered, e.g., by subcutaneous or intramuscular injection using a needle and syringe, or a needle-less injection device. Alternatively, the vaccine formulation is
30 administered intranasally, either by drops, large particle aerosol (greater than about 10 microns), or spray into the upper respiratory tract or small particle aerosol (less than 10 microns) or spray into the lower respiratory tract. While any of the above routes of delivery results in an immune response, intranasal administration confers the added benefit of eliciting

mucosal immunity at the site of entry of many viruses, including alphaviruses, for example CHIKV.

Thus, the invention also comprises a method of formulating a vaccine or antigenic composition that induces immunity to an infection or at least one symptom thereof to a mammal, comprising adding to said formulation an effective dose of VLPs, e.g. CHIKV VLP. In one embodiment, the infection is an alphavirus infection, for example, but not limited to, Chikungunya virus, Sindbis virus, Eastern equine encephalitis (EEE) virus, Western equine encephalitis (WEE) virus, and Venezuelan equine encephalitis (VEE) virus.

In certain cases, stimulation of immunity with a single dose is preferred, however additional dosages can be also be administered, by the same or different route, to achieve the desired effect. In neonates and infants, for example, multiple administrations may be required to elicit sufficient levels of immunity. Administration can continue at intervals throughout childhood, as necessary to maintain sufficient levels of protection against infections. Similarly, adults who are particularly susceptible to repeated or serious infections, such as, for example, health care workers, day care workers, family members of young children, the elderly, and individuals with compromised cardiopulmonary function or immune systems may require multiple immunizations to establish and/or maintain protective immune responses. Levels of induced immunity can be monitored, for example, by measuring amounts of neutralizing secretory and serum antibodies, and dosages adjusted or vaccinations repeated as necessary to elicit and maintain desired levels of protection.

Prime Boost

The present methods also include a variety of prime-boost regimens. In these methods, one or more priming immunizations is followed by one or more boosting immunizations. The actual immunogenic composition can be the same or different for each immunization and the type of immunogenic composition (e.g., containing protein or expression vector), the route, and formulation of the immunogens can also be varied.

For example, in one embodiment, the prime comprises administering a DNA or gene-based vaccine as described herein and the boost comprises administering a VLP as described herein. In another embodiment, the prime comprises administering a VLP as described herein and the boost comprises administering a DNA or other gene-based vaccine as described herein.

One useful prime-boost regimen provides for two priming immunizations, four weeks apart, followed by two boosting immunizations at 4 and 8 weeks after the last priming immunization. It should also be readily apparent to one of skill in the art that there are several

permutations and combinations that are encompassed using the DNA, bacterial and viral expression vectors of the invention to provide priming and boosting regimens.

Methods of administering a composition comprising VLPs and/or DNA vaccines (vaccine and/or antigenic formulations) include, but are not limited to, parenteral

5 administration (e.g., intradermal, intramuscular, intravenous and subcutaneous), epidural, and mucosal (e.g., intranasal and oral or pulmonary routes or by suppositories). In a specific embodiment, compositions of the present invention are administered intramuscularly, intravenously, subcutaneously, transdermally or intradermally. The compositions may be administered by any convenient route, for example by infusion or bolus injection, by
10 absorption through epithelial or mucocutaneous linings (e.g., oral mucous, colon, conjunctiva, nasopharynx, oropharynx, vagina, urethra, urinary bladder and intestinal mucosa, etc.) and may be administered together with other biologically active agents. In some embodiments, intranasal or other mucosal routes of administration of a composition comprising VLPs of the invention may induce an antibody or other immune response that is
15 substantially higher than other routes of administration. In another embodiment, intranasal or other mucosal routes of administration of a composition comprising VLPs of the invention may induce an antibody or other immune response that will induce cross protection against other strains of the virus. Administration can be intramuscular, subdermal, intraperitoneal. In one preferred embodiment, the administration is intramuscular.

20 In yet another embodiment, the vaccine and/or antigenic formulation is administered in such a manner as to target mucosal tissues in order to elicit an immune response at the site of immunization. For example, mucosal tissues such as gut associated lymphoid tissue (GALT) can be targeted for immunization by using oral administration of compositions which contain adjuvants with particular mucosal targeting properties. Additional mucosal
25 tissues can also be targeted, such as nasopharyngeal lymphoid tissue (NALT) and bronchial-associated lymphoid tissue (BALT).

Vaccines and/or antigenic formulations of the invention may also be administered on a dosage schedule, for example, an initial administration of the vaccine composition with subsequent booster administrations. In particular embodiments, a second dose of the
30 composition is administered anywhere from two weeks to one year, preferably from about 1, about 2, about 3, about 4, about 5 to about 6 months, after the initial administration. Additionally, a third dose may be administered after the second dose and from about three months to about two years, or even longer, preferably about 4, about 5, or about 6 months, or about 7 months to about one year after the initial administration. The third dose may be

optionally administered when no or low levels of specific immunoglobulins are detected in the serum and/or urine or mucosal secretions of the subject after the second dose. In a preferred embodiment, a second dose is administered about one month after the first administration and a third dose is administered about six months after the first administration.

5 In another embodiment, the second dose is administered about six months after the first administration. In another embodiment, said VLPs of the invention can be administered as part of a combination therapy. For example, VLPs of the invention can be formulated with other immunogenic compositions, antivirals and/or antibiotics. A VLP may be administered concurrently, subsequent to, or sequentially with another immunogenic composition,
10 antiviral, antibiotic, or any other agent that prevents or treats an alphavirus (e.g., Chikungunya infection).

The dosage of the pharmaceutical formulation can be determined readily by the skilled artisan, for example, by first identifying doses effective to elicit a prophylactic or therapeutic immune response, e.g., by measuring the serum titer of virus specific
15 immunoglobulins or by measuring the inhibitory ratio of antibodies in serum samples, or urine samples, or mucosal secretions. Said dosages can be determined from animal studies. A non-limiting list of animals used to study the efficacy of vaccines include the guinea pig, hamster, ferrets, chinchilla, mouse and cotton rat, and non-human primates. Most animals are not natural hosts to infectious agents but can still serve in studies of various aspects of the
20 disease. For example, any of the above animals can be dosed with a vaccine candidate, e.g. VLPs of the invention, to partially characterize the immune response induced, and/or to determine if any neutralizing antibodies have been produced. For example, many studies have been conducted in the mouse model because mice are small size and their low cost allows researchers to conduct studies on a larger scale.

25 In addition, human clinical studies can be performed to determine the preferred effective dose for humans by a skilled artisan. Such clinical studies are routine and well known in the art. The precise dose to be employed will also depend on the route of administration. Effective doses may be extrapolated from dose-response curves derived from in vitro or animal test systems.

30 As also well known in the art, the immunogenicity of a particular composition can be enhanced by the use of non-specific stimulators of the immune response, known as adjuvants. Adjuvants have been used experimentally to promote a generalized increase in immunity against unknown antigens (e.g., U.S. Pat. No. 4,877,611). Immunization protocols have used adjuvants to stimulate responses for many years, and as such, adjuvants are well known to

one of ordinary skill in the art. Some adjuvants affect the way in which antigens are presented. For example, the immune response is increased when protein antigens are precipitated by alum. Emulsification of antigens also prolongs the duration of antigen presentation. The inclusion of any adjuvant described in Vogel et al., "A Compendium of Vaccine Adjuvants and Excipients (2nd Edition)," herein incorporated by reference in its entirety for all purposes, is envisioned within the scope of this invention.

Exemplary adjuvants include complete Freund's adjuvant (a non-specific stimulator of the immune response containing killed *Mycobacterium tuberculosis*), incomplete Freund's adjuvants and aluminum hydroxide adjuvant. Other adjuvants comprise GMCSP, BCG, aluminum hydroxide, MDP compounds, such as thur-MDP and nor-MDP, CGP (MTP-PE), lipid A, and monophosphoryl lipid A (MPL). RIBI, which contains three components extracted from bacteria, MPL, trehalose dimycolate (TDM) and cell wall skeleton (CWS) in a 2% squalene/Tween-80 emulsion also is contemplated. MF-59, Novasomes.RTM., MHC antigens may also be used.

The VLPs of the invention can also be formulated with "immune stimulators." These are the body's own chemical messengers (cytokines) to increase the immune system's response. Immune stimulators include, but not limited to, various cytokines, lymphokines and chemokines with immunostimulatory, immunopotentiating, and pro-inflammatory activities, such as interleukins (e.g., IL-1, IL-2, IL-3, IL-4, IL-12, IL-13); growth factors (e.g., granulocyte-macrophage (GM)-colony stimulating factor (CSF)); and other immunostimulatory molecules, such as macrophage inflammatory factor, Flt3 ligand, B7.1; B7.2, etc. The immunostimulatory molecules can be administered in the same formulation as the VLPs, or can be administered separately. Either the protein or an expression vector encoding the protein can be administered to produce an immunostimulatory effect. Thus in one embodiment, the invention comprises antigenic and vaccine formulations comprising an adjuvant and/or an immune stimulator.

Methods of Delivery

The VLPs of the invention are useful for preparing compositions that stimulate an immune response. Such compositions are useful for the treatment or prevention of a viral infection (e.g., a CHIKV or other alphavirus infection). Both mucosal and cellular immunity may contribute to immunity to infectious agents and disease. In one embodiment, the invention encompasses a method of inducing immunity to a viral infection, for example

Chikungunya virus infection in a subject, by administering to the subject a Chikungunya virus VLP or a DNA vaccine.

The invention also provides a method to induce immunity to viral infection or at least one symptom thereof in a subject, comprising administering at least one effective dose of a VLP or DNA vaccine as described herein, for example a VLP comprising one or more viral proteins, for example one or more CHIKV virus envelope proteins or a DNA vaccine comprising a nucleic acid segment encoding an alphavirus capsid protein or one or more alphavirus envelope proteins, or fragments thereof. In certain cases, the VLP further comprises a virus capsid protein. In another embodiment, the method comprises inducing immunity to a viral infection, e.g. CHIKV infection or at least one symptom thereof by administering said formulation in multiple doses.

VLPs of the invention can induce substantial immunity in a vertebrate (e.g. a human) when administered to said vertebrate. The substantial immunity results from an immune response against VLPs of the invention that protects or ameliorates infection or at least reduces a symptom of infection in said vertebrate. In some instances, if the said vertebrate is infected, said infection will be asymptomatic. The response may be not a fully protective response. In this case, if said vertebrate is infected with an infectious agent, the vertebrate will experience reduced symptoms or a shorter duration of symptoms compared to a non-immunized vertebrate.

In one embodiment, the invention comprises a method of inducing substantial immunity to alphavirus infection or at least one symptom thereof in a subject, comprising administering at least one effective dose of a VLP and /or a DNA vaccine comprising a nucleic acid segment encoding an alphavirus capsid protein or one or more alphavirus envelope proteins, or fragments thereof. In particular embodiments, the infection is CHIKV and the VLP comprises one or more CHIKV envelope protein as described herein. In another embodiment, the invention comprises a method of vaccinating a mammal against an alphavirus comprising administering to said mammal a protection-inducing amount of VLPs or DNA vaccines comprising at least one alphavirus protein. In one embodiment, said method comprises administering DNA vaccines comprising capsid, E3, E2, 6K and E1. In another embodiment, said method comprises administering DNA vaccines comprising E3, E2, 6K and E1. In another embodiment, said method comprises administering DNA vaccines comprising C-Env₃₇₉₉₇ as set forth as SEQ ID NO:1. In another embodiment, said method comprises administering DNA vaccines comprising Env₃₇₉₉₇ as set forth as SEQ ID NO:19. In another embodiment, said method comprises administering DNA vaccines comprising C-

Env_{OPY-1} as set forth as SEQ ID NO:3. In another embodiment, said method comprises administering DNA vaccines comprising Env_{OPY-1} as set forth as SEQ ID NO:20. In one embodiment, said method comprises administering VLPs comprising capsid, E3, E2, 6K and E1. In another embodiment, said method comprises administering VLPs comprising E3, E2, 6K and E1. In one embodiment, said method comprises administering VLPs comprised of Chikungunya virus envelope proteins.

In another embodiment, the invention comprises a method of inducing a protective cellular response to a viral infection or at least one symptom thereof in a subject, comprising administering at least one effective dose of a DNA vaccine or a VLP.

As mentioned above, the VLPs of the invention prevent or reduce at least one symptom of an infection in a subject. A reduction in a symptom may be determined subjectively or objectively, e.g., self assessment by a subject, by a clinician's assessment or by conducting an appropriate assay or measurement (e.g. body temperature), including, e.g., a quality of life assessment, a slowed progression of viral infection or additional symptoms, a reduced severity of viral symptoms or a suitable assays (e.g. antibody titer and/or T-cell activation assay). The objective assessment comprises both animal and human assessments.

The invention also provides assays to identify inhibitors of viral entry comprising, in at least one embodiment, genetically modified target cells expressing at least one Chikungunya viral receptor, together with any co-receptors which might be required for infection or entry. These cells are genetically modified in the sense that they express a reporter gene, such as an affinity tag, a fluorogenic protein or an enzyme able to convert substrates into fluorogenic, chromogenic or luminometric products. Coupling this type of reporter signal to an inhibition of viral infection is accomplished by arranging the expression of the reporter gene to be strongly decreased (downregulated) upon infection with the virus of interest. In principle, this can be ensured by any suitable means, but especially preferred are:

The reporter gene product itself is fused to a cellular protein which, upon infection with the virus of interest is itself downregulated. For example, the reporter gene product can be fused to the corresponding viral receptor, which in many cases is downregulated upon infection.

Thus in one aspect a compound library may be screened for the ability to inhibit the infection of cells with Chikungunya virus (CHIKV). An appropriate indicator cell line is generated that stably expresses a reporter gene. In one example, these cells are seeded in microtiter plates and incubated with CHIKV particles in presence of different compounds, e.g., antibodies, in each well. Upon infection, the fusion protein is downregulated due to the

expression of the viral genes. Consequently, only cells that have not been infected with CHIKV will express the reporter gene. Thus, wells that exhibit a positive reporter signal contain compounds that inhibit infection. Variations and modifications of these assays will be apparent from the relevant sections of the description which explain individual parts of the assay in more detail. Specifically, in one embodiment, the reporter gene can be expressed when infection occurs rather than the reporter gene being downregulated upon infection. In further embodiments, the viral particles are pseudotyped viral particles comprising one or more envelope protein and, optionally, the capsid protein from CHIKV.

In another embodiment, the invention provides methods for identifying inhibitors of viral entry using a reporter gene system as exemplified herein. Briefly, the invention provides recombinant lentiviral vectors expressing a reporter gene. Cells are incubated and co-transfected with an expression vector, e.g., Env₃₇₉₉₇, Env_{OPY-1}, and a reporter plasmid using a standard techniques.

Cells are plated into one day prior to infection. CHIKV Env-pseudotyped lentiviral vectors encoding the reporter gene are first titrated by serial dilution. Similar amounts of pseudotyped vectors are then incubated with the candidate inhibitors prior to adding the virus. Cells are then lysed using cell lysis buffer and the reporter gene activity is measured. Inhibitors of viral entry are identified based on the expression of the reporter gene.

KITS

The invention also provides for a pharmaceutical pack or kit comprising one or more containers filled with one or more of the ingredients of the vaccine formulations of the invention. In a preferred embodiment, the kit comprises two containers, one containing VLPs and the other containing an adjuvant. 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.

The invention also provides that the VLP formulation be packaged in a hermetically sealed container such as an ampoule or sachette indicating the quantity of composition. In one embodiment, the VLP composition is supplied as a liquid, in another embodiment, as a dry sterilized lyophilized powder or water free concentrate in a hermetically sealed container and can be reconstituted, e.g., with water or saline to the appropriate concentration for administration to a subject.

The invention also features a kit comprising a VLP as described herein. The

invention also features kits comprising a DNA vaccine as described herein and instructions for use.

The invention also features a kit comprising a VLP in a first container and a DNA vaccine in a second container, and instructions for use in a prime boost immunization.

5 The following examples are offered by way of illustration, not by way of limitation. While specific examples have been provided, the above description is illustrative and not restrictive. Any one or more of the features of the previously described embodiments can be combined in any manner with one or more features of any other embodiments in the present invention. Furthermore, many variations of the invention will become apparent to those
10 skilled in the art upon review of the specification. The scope of the invention should, therefore, be determined not with reference to the above description, but instead should be determined with reference to the appended claims along with their full scope of equivalents.

The practice of the present invention employs, unless otherwise indicated, conventional techniques of molecular biology (including recombinant techniques),
15 microbiology, cell biology, biochemistry and immunology, which are well within the purview of the skilled artisan. Such techniques are explained fully in the literature, such as, “Molecular Cloning: A Laboratory Manual”, second edition (Sambrook, 1989); “Oligonucleotide Synthesis” (Gait, 1984); “Animal Cell Culture” (Freshney, 1987); “Methods in Enzymology” “Handbook of Experimental Immunology” (Weir, 1996); “Gene
20 Transfer Vectors for Mammalian Cells” (Miller and Calos, 1987); “Current Protocols in Molecular Biology” (Ausubel, 1987); “PCR: The Polymerase Chain Reaction”, (Mullis, 1994); “Current Protocols in Immunology” (Coligan, 1991). These techniques are applicable to the production of the polynucleotides and polypeptides of the invention, and, as such, may be considered in making and practicing the invention. Particularly useful techniques for
25 particular embodiments will be discussed in the sections that follow.

The following examples are put forth so as to provide those of ordinary skill in the art with a complete disclosure and description of how to make and use the assay, screening, and therapeutic methods of the invention, and are not intended to limit the scope of what the inventors regard as their invention.

EXAMPLES

Example 1: Lentiviral vectors pseudotyped with CHIKV envelope mediated entry through the same mechanism as wild type virus

5 To examine the mechanism and specificity of CHIKV cell entry, lentiviral vector reporters were pseudotyped with glycoproteins from different CHIKV strains that mediate entry into permissive cells. The CHIKV spike on the virion surface is formed by three E1-E2 heterodimers, where E1 glycoproteins mediate fusion and E2 glycoproteins interact with the host receptor. CHIKV E genes expressing the native polypeptide, E3-E2-6K-E1 polyprotein, 10 for the 37997 and for LR2006 OPY-1 strains were inserted into an expression vector (E37997 and EOPY-1) (Figure 1A, Figures 6, 7A, 7B, and 8A-8C). The incorporation of the two CHIKV Es into the pseudotyped lentiviral vectors was verified by buoyant density gradient sedimentation of the virus. Both CHIKV E and HIV-1 Gag had the same buoyant density as lentivirus particles (Figure 5). The 37997 and LR2006 OPY-1 CHIKV pseudotyped 15 lentiviral vectors infected several permissive cell lines (Sourisseau *et al.*, *PLoS. Pathog.* **3**, e89 (2007)) as measured by luciferase reporter activity, while a control devoid of CHIKV envelope proteins did not infect these cell lines (Figure 1B, left), and infectivity was dose-dependent (Figure 1B, right).

 To determine whether entry occurred through the same mechanism as native virus, the 20 pH and endosome dependence of entry was analyzed as described previously (Yang *et al.*, *J. Virol.* **78**, 5642 (2004)). CHIKV infects cells through a process of pH-dependent cell fusion. Thus, addition of ammonium chloride or chloroquine, which prevents acidification of the endosome, caused a dose-dependent reduction in CHIKV pseudotyped vector entry (Figure 1C). Similar inhibition of entry was observed with VSV- G, known to enter in this fashion, 25 but not with amphotropic murine leukemia virus (MuLV) glycoprotein 70, which enters in a pH-independent fashion. These findings demonstrated that lentiviral vectors pseudotyped with CHIKV envelope mediated entry through the same mechanism as wild type virus. Sera from mice injected with a CHIKV strain were next examined. Incubation of immune sera with the CHIKV pseudotyped lentiviral vector but not VSV-G pseudotyped vector inhibited 30 entry (Figure 1D). The specificity and potency of neutralizing antibodies could therefore be quantified without exposure to infectious virus.

Example 2: VLPs have morphology of wild type virus

CHIKV encodes 4 nonstructural proteins, NS1, NS2, NS3 and NS4, which are involved in virus replication, and 5 structural proteins, which consist of capsid (C) and envelope proteins (E; E1, E2, E3 and 6K) that are synthesized as polyproteins and are cleaved by capsid autoprotease and signalases (Strauss, *Microbiol. Rev.* **58**, 491 (1994)).

Eukaryotic expression vectors encoding C-E3-E2-6K-E1 from strains 37997 and LR2006 OPY-1 (C-E37997 and C-EOPY-1) were analyzed for their ability to give rise to VLP. The plasmids C-E37997 or C-EOPY-1 or the expression vectors described above, E37997 or EOPY-1 (Figure 2A, upper panel), were transfected into human embryonic kidney (293T) cells, and expression was confirmed by Western blotting (Figure 2A, lower panel). C and E1/E2 proteins were detected in the supernatant after transfection of the C-E37997 or C-EOPY-1 vector, suggesting that CHIKV VLPs had been generated. VLPs were purified by buoyant density gradient sedimentation. The yield of VLPs from strain 37997 was 10-20 mg/L, approximately 100 times higher than that from strain LR2006 OPY-1; strain 37997 was therefore chosen for further VLP characterization and development. Fractionation of clarified supernatant showed peak incorporation of E1/E2 at a density of 1.2 g/ml (Figure 2B, left), comparable to the density of wild type CHIKV. Examination of the purified fraction from strain 37997 by electron microscopy revealed VLPs with the same morphologic appearance as wild type virus (Figure 2B, right).

Cryoelectron microscopy and three dimensional image reconstruction assuming icosahedral symmetry showed that the VLPs had an external diameter of 65 nm and a core diameter of 40 nm (Figure 2C, left). The potent immunogenic E1/E2 glycoproteins are organized into 240 heterodimers, assembled into 80 glycoprotein spikes arranged with T=4 quasi symmetry on the surface of the VLPs (Figure 2C, left), closely similar to the structure of Sindbis virus (Figure 2C, right). In addition, the organization of the nucleocapsid core is also remarkably similar to that of other alphaviruses.

Example 3: VLPs induced a more potent neutralizing antibody response to CHIKV than DNA vaccines

The immunogenicity of DNA and VLP vaccines was determined in mice immunized with DNA vaccines encoding C-E or E (strains 37997 and LR2006 OPY-1) or VLPs from strain 37997 (VLP37997) in the presence or absence of Ribi adjuvant. Mice injected with VLPs with adjuvant generated the highest titer neutralizing responses against both the homologous strain 37997 (Figure 3A, right panel; IC₅₀, 1:10,703) and the heterologous strain

LR2006 OPY-1 (Figure 3B, right panel; IC₅₀, 1:54,600). While immunization with the plasmids encoding C-E and E from both strains elicited neutralizing responses, these responses were 100-fold lower than the VLP- immunized mice (Figure 3A, B; left panel). These results indicate that VLPs elicited a more potent neutralizing antibody response than DNA vaccines.

To characterize VLP-induced immune responses in a model with strong predictive value for humans, rhesus macaques were immunized with VLPs. Monkeys were injected with VLP37997 or PBS alone as a control. Sera from immunized and control monkeys were tested against CHIKV strain 37997 and LR2006 OPY-1 pseudotyped lentiviral vectors. All non-human primates (NHP) immunized with VLPs developed substantial neutralizing activity to both homologous and heterologous strains after primary immunization that increased after boosting (Figure 3C; left panel: strain 37997, right panel: strain LR2006 OPY-1). To confirm that these antibodies neutralized infectious virus, a plaque reduction neutralization test (PRNT) was performed against the CHIKV LR2006 OPY-1. The antisera from the immunized monkeys elicited neutralizing antibody responses against LR2006 OPY-1 at titers that exceeded 1:40,000 (Figure 3D). These data suggested that neutralizing antibodies using pseudotyped lentiviral vectors correlated with the PRNT assay, and that all immunized monkeys generated potent neutralizing antibody responses against CHIKV.

Example 4: Primate VLP immunization protected against viremia and inflammatory consequences of CHIKV infection

The ability of the VLP vaccine to protect against infection was determined by intravenous challenge of monkeys immunized with VLPs or controls using a high titer LR2006 OPY-1 virus stock 15 weeks after the final immunization. Similar to humans, infection in the NHP resulted in non-lethal viremia and a pro-inflammatory response as measured by an increase in monocyte counts. The control monkeys showed viremia beginning at 6 hours and lasting until 72 hours after challenge, while all of the immunized monkeys controlled the challenge virus completely (Figure 4A). Similarly, the monocyte counts in control monkeys increased markedly relative to vaccinated monkeys by 4 days after challenge (Figure 4B, Control vs. VLPs; $p = 0.0036$). These data indicated that immunization protected against viremia as well as the inflammatory consequences of infection. To define the mechanism of protection in these animals, the question of whether immune IgG could protect against lethal challenge was examined using an adoptive transfer model.

Example 5: Humoral immune responses induced by CHIKV VLPs conferred protection against CHIKV infection

Previous studies have shown that immunodeficient mice with defective type-I IFN signaling developed severe infection, displaying symptoms and tissue tropism analogous to humans, and providing a model to evaluate immune mechanisms of protection. Purified total IgG from immune or control monkeys was passively transferred into these mice. The recipient mice were challenged intradermally 24 hours after IgG transfer with a lethal dose of LR2006 OPY-1. Recipients of purified CHIKV immune IgG demonstrated no detectable viremia after infection and were completely protected from lethality (Figures 4C, D). In contrast, all mice that received purified IgG from control monkeys showed severe infection and viremia, and all died. These results indicate that humoral immune responses induced by CHIKV VLPs conferred protection against CHIKV infection.

As reported herein, VLPs and plasmid DNA vaccines against CHIKV were evaluated for their ability to elicit cross-strain neutralizing antibodies. Immunization with VLPs showed cross- strain reactivity and 100-fold higher titers than DNA vaccines, and monkeys showed protection against CHIKV infection at a dose higher than that likely to be encountered in the field. Moreover, passively transferred antibody from monkeys immunized with VLPs protected against a lethal challenge in a relevant murine model, which suggests that the humoral response is important for protection against CHIKV. The current outbreaks of CHIKV fever have occurred largely in Southern Asia and underscore the need for a human vaccine. These infections represent the spread of a virus first recognized in Kenya in 2004 before dissemination to several islands in the Indian Ocean in 2005-2006. The Reunion Island outbreak alone infected 244,000 people with an overall seroprevalence of 35%. The virus then spread to other continents, and by 2008 was reported in 37 countries (http://www.cdc.gov/ncidod/dvbid/chikungunya/CH_GlobalMap.html) with an estimated 1.4 – 6.5 million cases in India, Africa, Europe and Southeast Asia.

In 2009 the number of cases has continued to increase, in part because the current epidemic strain of CHIKV has adapted to a new vector, the Asian tiger mosquito, *Ae. albopictus*, which can survive in more temperate climates, including Europe and the United States. CHIKV continues to cause substantial morbidity and has resulted in significant economic losses. While there were no reports of mortality in previous chikungunya epidemics, more than 260 deaths during the latest outbreak were directly attributed to the virus. To date, there has been limited success in developing a safe and effective CHIKV vaccine. A live CHIKV vaccine candidate caused transient arthralgia in volunteers. Other

efforts, which include a live attenuated vaccine, a formalin-killed vaccine, a Venezuelan equine encephalitis/CHIKV chimeric live attenuated vaccine and a consensus- based DNA vaccine (Muthumani *et al.*, *Vaccine* **26**, 5128 (2008)) have not yet proven to be both safe and effective. Although CHIKV strains vary widely, individual strains are antigenically related, so a vaccine that works against heterologous strains may be achieved (Harrison et al., *Am. J Trop. Med. Hyg.* **16**, 786 (1967)). The safety and efficacy of VLP vaccines in general make them promising candidates for further study.

VLPs are known to be highly immunogenic and elicit higher titer neutralizing antibody responses than subunit vaccines based on individual proteins. Such VLPs authentically present viral spikes and other surface components in a repetitive array that effectively elicits recognition by B-cells to stimulate antibody secretion. This recognition leads to B cell signaling and MHC class II up-regulation that facilitates the generation of high titer specific antibodies. VLPs from other viruses, including hepatitis B virus (HBV) and human papillomavirus (HPV), elicit high titer neutralizing antibody responses that contribute to protective immunity in humans.

The vaccines described herein represent the first use of recombinant VLPs to prevent infection by alphaviruses. The spread of mosquito species worldwide has been aided by changes in trade, travel or global climate and may potentially cause other alphavirus outbreaks. This approach to vaccine development may prove useful for other alphaviruses of increasing concern, including Western, Eastern, and Venezuelan equine encephalitis viruses, o'nyong-nyong virus and Ross River virus.

The results reported herein were obtained using the following methods and materials.

Vector construction

Plasmids encoding the structural polyproteins C, E1, E2, E3 and 6K (strains 37997 and LR2006 OPY-1, GenBank EU224270)(Figure 25)and EU224268 (Figure 24), respectively) were synthesized as previously described (Yang *et al.*, *Science* **317**, 825 (2007)) (GeneArt, Regensburg, Germany). Plasmids encoding the polyproteins E3, E2, 6K, and E1 were amplified by PCR using the sense primer 5' GCTCTAGACACCATGAGCCTCGCCCTCCCGGTCTTG 3' and antisense primer 5' TGGATCCTCATTAGTGCCTGCTAAACGACA 3' (37997) and the sense primer 5' GCTCTAGACACCATGAGTCTTGCCATCCCAGTTATG 3' and antisense primer 5' TGGATCCTCATTAGTGCCTGCTGAACGACA 3' (LR2006 OPY-1). XbaI and BamHI sites were inserted for cloning. Each fragment was digested with XbaI/BamHI and inserted into a

eukaryotic expression vector under the control of a cytomegalovirus enhancer/promoter, CMV/R (Yang *et al.*, *Science* **317**, 825 (2007)) (C-E37997, C-EOPY-1, E37997^{and} EOPY-1). To confirm expression of CHIKV C and E proteins, 293T cells were transfected using a FuGENE™ 6 Transfection Reagent kit (Roche Diagnostics GmbH, Germany) with 3 µg of the plasmid DNAs, following the manufacturer's recommendations.

Cell culture

293T and 293A (human embryonic kidney cells), Vero (African green monkey kidney epithelial cells), HeLa (human cervical adenocarcinoma), A549 (human lung carcinoma) and BHK (baby hamster kidney cells) were cultured in Dulbecco's modified Eagle's medium (DMEM; GIBCO BRL) containing 10% heat-inactivated fetal bovine serum (FBS) (GIBCO BRL).

Production of pseudotyped lentiviral vectors

Lentiviral vectors expressing glycoproteins from different CHIKV strains were created. The recombinant lentiviral vectors expressing a luciferase reporter gene were produced as previously described (Naldini *et al.*, *Proc. Natl. Acad. Sci. USA* **93**, 11382 (1996), Yang *et al.*, *Science* **317**, 825 (2007)). Briefly, 293T cells were co-transfected with 500 ng CHIKV E plasmid from either strain (E37997^{or} EOPY-1), 7 µg of a transducing vector encoding a luciferase reporter gene (pHR'CMV-luciferase plasmid), and 7 µg of a packaging plasmid expressing human immunodeficiency virus-1 (HIV-1) structural proteins (pCMVΔR8.2). 2 µg of vesicular stomatitis virus glycoprotein (VSV-G), 2 µg of pNGVL-4070A amphotropic MuLV gp70 expression vector or 500 ng of empty vector served as positive and negative controls for these pseudotyped reporters respectively. After a calcium phosphate transfection (Invitrogen, Carlsbad, CA) overnight, the culture media was replenished with fresh media. 48 hours later, supernatants were harvested, filtered through a 0.45 µm syringe filter, stored in aliquots, and frozen at -80°C. The viruses were standardized by the amount of HIV-1 Gag p24. CHIKV pseudotyped lentiviral vectors harvested 72 h after transfection were normalized according to HIV-1 Gag p24 levels before infection, as previously described (Yang *et al.*, *Science* **317**, 825 (2007)).

Neutralization of CHIKV E pseudotyped lentiviral vectors by mouse and monkey antisera

The neutralization assay was performed as described previously (Yang *et al.*, *Science* **317**, 825 (2007)). A total of 10^4 293A cells were plated into each well of a 96-well dish one day prior to infection. CHIKV E-pseudotyped lentiviral vectors encoding luciferase were first titrated by serial dilution. Similar amounts of pseudotyped lentiviral vectors (with p24 levels of approximately 50 ng/ml) were then incubated with the indicated dilutions of mouse antisera for 60 minutes at room temperature prior to adding the virus: sera solution to 293A cells (10^4 cells/well in a 96-well dish, 50 μ l/well, in triplicate). Sera from non-immune mice or monkeys were used as a negative control. After a 24 hour incubation, cells were lysed using cell lysis buffer (Cell Signal) and the luciferase activity was measured using Microbeta® JET (PerkinElmer, Turku, Finland) following incubation with "Luciferase assay reagent" (Promega, Madison, WI), according to the manufacturer's protocol. Inhibition values were calculated as follows: inhibition (%) = [1 - (luciferase activity (cps) in pseudotyped lentiviral vector infected cells incubated with the indicated dilutions of mouse antisera) / (luciferase activity (cps) in pseudotyped lentiviral vector infected cells incubated with the same dilutions of non-immune mouse serum)] $\times$ 100. The IC_{50} was calculated with Prism software (version 5).

Electron microscopy

The morphology of the VLPs was examined by the Image Analysis Laboratory at the National Cancer Institute. VLPs were purified by Optiprep density centrifugation and were then fixed in 4% formaldehyde in PBS. Negative-stain electron microscopy for viral diagnosis has been described previously (Palmer and Martin, *Electron Microscopy in Viral Diagnosis* (CRC Press, Boca Raton, FL, 1988)). Briefly, 1.0 μ l of the sample was placed onto a carbon-coated Formvar-filmed copper grid (Tousimis Research Corp., Rockville, MD) and VLPs allowed to attach. The VLPs were negatively stained by addition of 2 μ l of 1% PTA solution (phosphotungstic acid, pH 7.0) (Fisher Scientific Co., Fairlawn, NJ). The grid was then examined by electron microscope (Hitachi H7000, Tokyo, Japan) operated at 75 kV. Digital images were taken by a CCD camera (AMT, Danvers, MA).

Cryo-electron microscopy and image analysis

Chikungunya VLPs were flash-frozen on holey grids in liquid ethane. Images were recorded at 47K magnification with a CM300 FEG microscope with electron dose levels of approximately $20 \text{ e}^+/\text{\AA}^2$. All micrographs were digitized at $6.35 \text{ }\mu\text{m pixel}^{-1}$ using a
5 Nikon scanner. Individual particle images were boxed using the program e2boxer in the EMAN2 package (Tang *et al.*, *J Struct. Biol.* **157**, 38 (2007)). CTF parameters were determined and phases were flipped using the CTFIT program from the EMAN package (Ludtke *et al.*, *J Struct. Biol.* **128**, 82 (1999)). An initial model was constructed in EMAN using assigned 2-, 3-, and 5-fold views and was refined in EMAN assuming icosahedral
10 symmetry. The number of particles incorporated into the final reconstruction was 1489, giving a final resolution of $18 \text{ }\text{\AA}$ based on a 0.5 Fourier shell correlation threshold.

Buoyant density gradient sedimentation analysis and purification of VLPs

Buoyant density gradient analysis and purification of VLPs was performed as described
15 previously (Akahata *et al.*, *J. Virol.* **79**, 626 (2005)). Briefly, a 293-derived suspension cell line, 293F (2.5×10^8 cells) (Invitrogen) was transfected with 293fectin transfection reagent (Invitrogen) and $125 \text{ }\mu\text{g}$ of C-E37997 plasmid following the manufacturer's recommendations. The supernatants were harvested 72 h after transfection and filtered through a $0.45 \text{ }\mu\text{m}$ pore size filter, then layered onto a 60% Optiprep (Iodixanol) medium (Invitrogen) and centrifuged at
20 $50,000 \times g$ for 1.5 h with a Surespin 630 rotor (Sorvall). The supernatants were removed to leave 4 ml above the virus band and mixed to a 20% final concentration of OptiPrep. A density gradient was formed by centrifugation at $360,000 \times g$ for 3.5 hr with an NVT100 rotor (Beckman). $500 \text{ }\mu\text{l}$ of each fraction was collected, weighed, and the densities of the fractions were plotted. $20 \text{ }\mu\text{l}$ of each fraction was separated on a 4%-15% SDS-PAGE gel,
25 transferred onto an Immobilon-P membrane, and blotted with sera from mice injected with the CHIKV strain S-27 (ATCC, VR-1241AF) and goat anti-mouse immunoglobulins linked to horseradish peroxidase (Santa Cruz Biotechnology).

Immunizations and challenge of mouse and monkeys

30 Nineteen μg of VLPs (equivalent to approximately $10 \text{ }\mu\text{g}$ of E1/E2) in $60 \text{ }\mu\text{l}$ normal saline were mixed with $60 \text{ }\mu\text{l}$ of Ribi solution (Sigma Adjuvant system, Sigma-Aldrich) per mouse following the manufacturer's recommendations. Female 6- to 8-week-old BALB/c mice were injected in the right and left quadriceps muscles with VLPs in normal saline or Ribi in $120 \text{ }\mu\text{l}$ total volume, two times at weeks 2 and 6. For DNA vaccination

groups, the mice were injected in the right and left quadriceps muscles with a total of 15 µg of purified plasmid C-

E37997, E37997, C-EOPY-1 or EOPY-1 suspended in 100 µl of normal saline three times at weeks 0, 3 and 6. Five mice/group were injected. 10 days after the last injection, sera and spleen

5 were collected.

In the monkey experiments, rhesus macaques (*Macaca mulatta*) weighing 3-4 kg were injected intramuscularly in the anterior quadriceps with either twenty µg of VLPs in 1 ml PBS (VLP group) or 1 ml PBS alone (control group) at weeks 0, 4 and 24. Six monkeys/group were injected. Blood was collected to measure antibody titers on days -14, 0, 10, 28, 38, 56, 70, 10 161 and 178. The monkeys (n=3 per group, randomly selected from each group) were challenged with 10¹⁰ PFU of CHIKV (strain LR2006 OPY-1) by intravenous injection. Blood was collected to measure viremia at 0, 6, 24, 48, 72, 96, 120 and 168 hours. The monkeys were sacrificed at 168 h after challenge. The whole blood cells were measured using a hematology analyzer (IDEXX Laboratories, Inc., Westbrook, Maine). Bleeds were EDTA- 15 anticoagulated using 20-22 gauge needles and either syringes or vacuum tubes. The maximum blood volume removed did not exceed 20% (12 ml/kg) per month, with no more than 15% (9 ml/kg) removed during any single draw.

All animal experiments were reviewed and approved by the Animal Care and Use Committee, Vaccine Research Center (VRC), National Institute of Allergy and Infectious Diseases 20 (<http://www.niaid.nih.gov/vrc>) and performed in accordance with all relevant federal and National Institutes of Health guidelines and regulations.

Virus preparation

CHIKV (strain LR2006 OPY-1) was prepared and the virus titers were determined as 25 previously described (Tsetsarkin et al., PLoS. Pathog. 3, e201 (2007) and Pastorino et al., J Virol. Methods 124, 65 (2005)). Briefly, viral RNA transcribed from plasmid CHIK-LR ic was transfected into BHK-21 cells by electroporation. The supernatants from the transfected cells were aliquotted and the stock virus was titrated and tissue culture infectious dose 50% (TCID₅₀) endpoint titers were determined using Vero cells. To produce virus for 30 vertebrate challenge, C6/36 (*Aedes albopictus*) cells grown to confluence in T150 flasks were infected with stock virus at a multiplicity of infection of 0.03. Supernatants were harvested at 48 hrs post-infection, aliquotted and titrated to determine TCID₅₀ endpoint titers on Vero cells.

Plaque assay

Serum samples were tested for CHIKV neutralizing antibody by a standard plaque reduction neutralization test (PRNT). Briefly, monkey sera were heat inactivated at 56°C for 30 minutes and diluted in virus diluent (PBS/5% BSA). Diluted serum samples were mixed with an equal volume of 40 PFU CHIKV (strain LR2006 OPY-1) and incubated for 1 hr at 37°C. Six-well plates of confluent Vero cells were inoculated with 200 µl of the serum-virus mixtures in duplicate and incubated at 37°C for 1 hr. Plates were overlaid with 3 ml of medium containing 0.9% agarose (Lonza Rockland, Rockland, ME) and incubated at 37°C in a 5% CO₂ incubator for 2 days. A second overlay medium containing neutral red and 1% agarose was then added and the plates were incubated overnight before plaques were visualized and counted. The viremia in the monkeys after challenge was measured by plaque assay. Six-well plates of confluent Vero cells were inoculated with 200 µl of the serum-PBS mixtures in duplicate. The serum dilutions were 1:200, 1:400, 1:800, 1:1000, 1:10,000 and 1:100,000, since at lower dilutions toxicities were observed in the cells (detection limit 1:200 dilution = 1000 PFU/ml).

Passive transfer of immunoglobulin and challenge in IFN α / β R^{-/-} mice

IFN α / β R^{-/-} mice were kindly given by Robert Seder and Daniel D. Pinschewer. IgG was purified from the serum in monkeys immunized with CHIKV VLPs or injected with PBS (control) using a HiTrapTM Protein G HP column (GE Healthcare) following the manufacturer's recommendations. IgG was further purified using a Melon Gel IgG Purification Kit (Pierce) following the manufacturer's recommendations. Purified IgG was dialyzed 3 times against PBS. 2 mg of purified IgG (from approximately 200 µl of serum) was administered intravenously into each recipient IFN α / β R^{-/-} mouse by tail vein injection 24 h before challenge. The mice were challenged with 30 PFU of CHIKV (strain LR2006 OPY-1) by intradermal injection.

Detection of CHIKV RNA by quantitative RT-PCR

For RNA isolation, serum samples were spun down at 10,000 x g for 1 hr, liquid poured off and 1 ml of RNA-STAT 60 (Isotex Diagnostics, Friendswood, TX) added. Samples were then incubated at RT for 5 min and resuspended in 250 µl of chloroform by vortexing. The samples were spun down at 10,000 x g for 1 hr, the aqueous top-layer removed, 0.5 ml isopropanol and 10 µl tRNA (10 µg/ml) added and precipitated overnight

at -20°C. Samples were spun down for 1 hr, washed with cold 75% ethanol and spun again for another hour. RNA was resuspended in 30 µl RNase-free water. For RT-PCR, 10% RNA was added to TaqMan reagents (Applied Biosystems, Foster City, CA) along with primers and probe (listed below) and amplified in a 7700 Sequence Detection System (Applied Biosystems).

5 Briefly, the sample was reverse-transcribed at 48°C for 30 min., held at 95°C for 10 min, then run for 40 cycles of 95°C for 30 s and 60°C for 1 min. The signal was compared to a standard curve of known concentrations of plasmid containing the LR2006 OPY-1 sequence starting at 10⁷ down to 1 copy/mL and multiplied by 10, giving a detection range from 40-10⁸ copies/mL. All samples were performed in triplicate. The primers and probe were designed to
10 bind to a highly conserved region on the E1 structural protein gene. Primer sequences: CHIK-F 5' AAGCTCCGCGTCCTTTACCAAG 3' and CHIK-R 5' CCAAATTGTCCTGGTCTTCCT3'. Probe sequence: CHICK-P FAM-CCAATGTCTTCAGCCTGGACACCTTT-TAMRA as described previously (Huang et al., *J. Virol.* **78**, 12557 (2004); Pastorino et al., *J Virol. Methods* 124, 65 (2005)).

15

Other Embodiments

From the foregoing description, it will be apparent that variations and modifications may be made to the invention described herein to adopt it to various usages and conditions. Such embodiments are also within the scope of the following claims.

20

The recitation of a listing of elements in any definition of a variable herein includes definitions of that variable as any single element or combination (or subcombination) of listed elements. The recitation of an embodiment herein includes that embodiment as any single embodiment or in combination with any other embodiments or portions thereof.

All patents and publications mentioned in this specification are herein incorporated by
25 reference to the same extent as if each independent patent and publication was specifically and individually indicated to be incorporated by reference.

What is claimed is:

1. A virus-like particle (VLP) comprising one or more Chikungunya virus structural polypeptides.

2. The VLP of claim 1, wherein the structural polypeptides are selected from the group consisting of capsid and envelope proteins E3, E2, 6K and E1.

3. The VLP of claim 1, wherein the VLP comprises envelop proteins E3, E2, 6K and E1.

4. The VLP of claim 1, wherein the VLP comprises a polyprotein comprising C-E3-E2-6K-E1.

5. An isolated polynucleotide encoding a virus-like particle of any of claims 1-5.

6. The isolated polynucleotide of claim 5, wherein the polynucleotide encodes a Chikungunya virus polyprotein comprising C-E3-E2-6K-E1.

8. An expression vector comprising a polynucleotide encoding one or more Chikungunya virus structural polypeptides.

9. The expression vector of claim 8, wherein the polynucleotide encodes one or more structural polypeptides selected from the group consisting of capsid (C) and envelope proteins E3, E2, 6K and E1.

10. The expression vector of claim 8, wherein the polynucleotide encodes envelop proteins E3, E2, 6K and E1.

11. The expression vector of claim 8, wherein the polynucleotide encodes a Chikungunya virus polyprotein comprising C-E3-E2-6K-E1.

12. The expression vector of claim 8, wherein the expression vector is capable of expression in a prokaryotic or eukaryotic cell.

13. The expression vector of claim 8, wherein the structural polyprotein is derived from Chikungunya strain 37997 or LR2006.

14. The expression vector of claim 8, wherein the vector comprises the CMV/R promoter.
15. The expression vector of claim 8, wherein the expression vector is C-E37997 or C-EOPY-1.
16. A prokaryotic or eukaryotic cell comprising the expression vector of any one of claims 8-15.
17. An immunogenic composition comprising an effective amount of a virus-like particle of claims 1-5.
18. An immunogenic composition comprising an effective amount of a VLP comprising a Chikungunya structural polyprotein comprising C-E3-E2-6K-E1 and an adjuvant.
19. An immunogenic composition comprising an effective amount of an expression vector of any of claim 8-15.
20. The immunogenic composition of any of claims 17 -19, wherein the VLP induces an immune response in a subject.
21. The immunogenic composition of any of claims 17 -19, wherein the immune response treats or prevents a Chikungunya infection in a subject.
22. The immunogenic composition of any of claims 17 -19, wherein the VLP induces antibodies against homologous or heterologous strains of Chikungunya.
23. The immunogenic composition of any of claims 17 -19, wherein the adjuvant is an immunostimulating agent.
24. The immunogenic composition of any of claims 17 -19, wherein the adjuvant is selected from the group consisting of Ribi, aluminum salts, muramyl peptides, bacterial cell wall components, and saponin adjuvants.

25. A vaccine comprising an effective amount of one or more Chikungunya virus structural polypeptides selected from the group consisting of capsid (C) and envelope proteins E1, E2, E3 and 6K.

5 26. A vaccine comprising an effective amount of a virus-like particle of any of claims 1-5 or comprising a polyprotein comprising C-E3-E2-6K-E1.

27. A vaccine comprising a polynucleotide encoding a Chikungunya structural polyprotein or fragment thereof.

10

28. The vaccine of claim 27, wherein the Chikungunya structural polyprotein is encoded by an expression vector of any of claims 8-15.

15

29. The vaccine of claim 27, wherein the expression vector comprises a CMV/R promoter.

30. The vaccine of claim 24, wherein the vaccine is a DNA vaccine.

20

31. A method of inducing an immune response against Chikungunya in a subject, the method comprising administering to the subject an effective amount of an immunogenic composition of any of claims 14-24.

25

32. The method of claim 31, wherein the immunogenic composition comprises one or more Chikungunya virus structural polypeptides selected from the group consisting of capsid (C) and envelope proteins E1, E2, E3 and 6K.

33. The method of claim 31, wherein the immunogenic composition comprises a polyprotein comprising C-E3-E2-6K-E1.

30

34. The method of claim 31, wherein the method induces neutralizing antibodies in a subject.

35. A method for treating or preventing a Chikungunya infection in a subject, the method comprising administering to the subject an effective amount of a vaccine of any one of claims 21-23 or an immunogenic composition of any one of claims 14-24.

5 36. The method of claim 31 or 35, wherein the vaccine or immunogenic composition is administered in one or more doses.

37. The method of claim 36, wherein the vaccine or immunogenic composition is administered in one or more priming immunizations and one or more boosting
10 immunizations.

38. The method of claim 37, wherein the priming immunizations are administered at one, two, three, four, five, six, seven or eight week intervals.

15 39. The method of claim 37, wherein the boosting immunizations are administered two weeks, one month, two months or three months after the priming immunization.

40. The method of claim 37, wherein the immunization protects the subject against viremia or the inflammatory consequences of infection.

20 41. The method of claim 35, wherein the method protected from lethality

42. A method for producing a virus-like particle, the method comprising expressing in a cell one or more Chikungunya structural protein capable of self-assembly to form a virus-like
25 particle.

43. The method of claim 42, the method further comprising isolating the virus-like particle.

30 44. The method of claim 42, wherein the Chikungunya structural proteins are selected from the group consisting of capsid (C) and envelope proteins E1, E2, E3 and 6K.

45. The method of claim 42, wherein the Chikungunya structural proteins are present in a Chikungunya structural polypeptide.

46. A virus-like particle (VLP) comprising one or more alphavirus structural polypeptides

47. The VLP of claim 42, wherein the structural polypeptide is a capsid or envelope polypeptide.

48. The VLP of claim 43, wherein the alphavirus is selected from the group consisting of: Chikungunya virus, Sindbis virus, Eastern equine encephalitis (EEE) virus, Western equine encephalitis (WEE) virus, and Venezuelan equine encephalitis (VEE) virus.

49. An isolated polynucleotide encoding a virus-like particle of any of claims 44-46.

50. An expression vector comprising a polynucleotide encoding one or more alphavirus structural polypeptides wherein the alphavirus is selected from the group consisting of Chikungunya virus, Sindbis virus, Eastern equine encephalitis (EEE) virus, Western equine encephalitis (WEE) virus, and Venezuelan equine encephalitis (VEE) virus.

51. An immunogenic composition comprising an effective amount of a virus-like particle of any of claims 44-46.

52. A vaccine comprising an effective amount of one or more alphavirus structural polypeptides or a polynucleotide encoding one or more alphavirus structural proteins, wherein the alphavirus is selected from the group consisting of Chikungunya virus, Sindbis virus, Eastern equine encephalitis (EEE) virus, Western equine encephalitis (WEE) virus, and Venezuelan equine encephalitis (VEE) virus.

53. A method of inducing an immune response against an alphavirus in a subject, the method comprising administering to the subject an effective amount of an immunogenic composition of claim 51.

54. The method of claim 53, wherein the immunogenic composition comprises one or more alphavirus structural polypeptides.

55. The method of claim 53, wherein the method induces neutralizing antibodies in the subject.

56. A method for treating or preventing an alphavirus infection in a subject, the method comprising administering to the subject an effective amount of a vaccine of claim 44 or an immunogenic composition of claim 47.

5 57. A kit comprising a VLP of any of claims 1-5, and instructions for use.

58. A kit comprising an immunogenic composition of any of claims 13-19 or 41-43, and instructions for use in a subject.

10 59. The kit of claim 58, wherein the immunogenic composition is provided in a first container and second immunogenic composition is provided in a second container, and instructions for use in a prime boost immunization.

15 60. The kit of claim 58, wherein the immunogenic composition in the second container comprises a VLP, viral polypeptide, or viral polynucleotide.

61. A method for identifying inhibitors of Chikungunya virus entry into a eukaryotic cell, the method comprising contacting a cell that expresses a Chikungunya virus receptor with a Chikungunya polypeptide selected from the group consisting of C, E3, E2, 6K, and E1 and a
20 candidate compound, and assaying for viral entry, wherein a candidate compound that reduces viral entry in the cell relative to a control cell is identified as an inhibitor of Chikungunya virus entry.

25 62. The method of claim 61, wherein the candidate inhibitor is an antibody, or fragment thereof or small molecule.

63. A method for identifying inhibitors of Chikungunya viral entry comprising:
contacting a cell that expresses a Chikungunya virus receptor with a candidate
inhibitor and a pseudotyped virus comprising a reporter gene; and
30 measuring expression of the reporter gene in the cell, wherein a compound that reduces expression of the reporter gene relative to a control cell is identified as inhibiting viral entry.

64. The method of claim 63, wherein the pseudotyped virus comprises one or more Chikungunya virus envelope proteins.

65. The method of claim 63, wherein the one or more envelope proteins are selected from the group consisting of E3, E2, 6K and E1.

66. The method of claim 63, wherein the pseudotyped virus is a lentivirus.

67. The method of claim 63, wherein the candidate inhibitor is an antibody, or fragment thereof or small molecule.

68. A virus-like particle (VLP) comprising one or more Chikungunya virus structural polypeptides for use in treating or preventing a Chikungunya infection.

69. A method for treating or preventing a Chikungunya infection, the method comprising administering a virus-like particle (VLP) comprising one or more Chikungunya virus structural polypeptides prior to, subsequent to, concurrent with, or in any other sequence with the administration of one or more of another immunogenic composition, antiviral, or antibiotic agent.