

INTEGRAL MEMBRANE PROTEIN DISPLAY ON POXVIRUS EXTRACELLULAR ENVELOPED VIRIONS

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BACKGROUND

[0001] Antibodies of defined specificity are being employed in an increasing number of diverse therapeutic applications. A number of methods have been used to obtain useful antibodies for human therapeutic use. These include chimeric and humanized antibodies, and fully human antibodies selected from libraries, *e.g.*, phage display libraries, or from transgenic animals. Immunoglobulin libraries constructed in bacteriophage can derive from antibody producing cells of naïve or specifically immunized individuals and could, in principle, include new and diverse pairings of human immunoglobulin heavy and light chains. Although this strategy does not suffer from an intrinsic repertoire limitation, it requires that complementarity determining regions (CDRs) of the expressed immunoglobulin fragment be synthesized and fold properly in bacterial cells. Many antigen binding regions, however, are difficult to assemble correctly as a fusion protein in bacterial cells. In addition, the protein will not undergo normal eukaryotic post-translational modifications. As a result, this method imposes a different selective filter on the antibody specificities that can be obtained. Alternatively, fully human antibodies can be isolated from libraries in eukaryotic systems, *e.g.*, yeast display, retroviral display, or expression in DNA viruses such as poxviruses. See, *e.g.*, U.S. Patent No. 7,858,559, and U.S. Patent Appl. Publication No. 2013-028892, which are incorporated herein by reference in their entireties.

[0002] Many important targets for therapeutic antibodies are integral membrane proteins (IMPs), *e.g.*, multi-pass membrane proteins (GPCRs, Ion Channels, etc.) that are difficult to express and purify in a conformationally-intact state. The absence of properly folded target proteins in an isolated state makes the identification and selection of antibodies to these targets challenging. While certain IMPs can be expressed on the surface of cells, *e.g.*, mammalian cells, whole cells are problematic for use in antibody discovery because they are

complex antigen mixtures, target expression can be low, and because certain display packages used to construct antibody libraries (*e.g.*, vaccinia virus antibody libraries) can bind to whole cells non-specifically. There remains a need for new methods to express and display target IMPs of interest in their native conformation at a sufficient concentration and with minimal competition from other cell proteins to allow for identification and selection of therapeutic antibodies and antibody-like molecules from display libraries.

SUMMARY

[0003] This disclosure provides compositions and methods for expressing and displaying isolated integral membrane proteins (IMPs) or fragments thereof in a native conformation for use in the screening, selecting, and identifying of antibodies or antibody-like molecules that bind to a target IMP of interest.

[0004] In certain embodiments, the disclosure provides an isolated polynucleotide that includes: a first nucleic acid fragment that encodes an integral membrane protein (IMP) or fragment thereof, where the IMP or fragment thereof includes at least one extra-membrane region, at least one transmembrane domain and at least one intra-membrane region, and where a portion of the first nucleic acid fragment encoding at least one intra-membrane region is situated at the 5' or 3' end of the first nucleic acid fragment; and a second nucleic acid fragment that encodes a vaccinia virus F13L protein or functional fragment thereof, where the second nucleic acid fragment is fused in frame to a portion of the first nucleic acid fragment that encodes an intra-membrane region of the IMP. According to these embodiments, a poxvirus infected cell containing the polynucleotide can express an IMP-F13L fusion protein as part of the outer envelope membrane of an extracellular enveloped virion (EEV). In certain aspects, the F13L protein or functional fragment thereof can include the amino acid sequence SEQ ID NO: 1 or a functional fragment thereof. In certain aspects the IMP is a multi-pass membrane protein comprising at least two, at least three, at least four, at least five, at least six or at least seven transmembrane domains. In certain aspects the IMP is a multi-pass membrane protein listed in Table 1.

[0005] In certain aspects the multi-pass IMP can have an odd number of transmembrane domains, the 5' end of the first nucleic acid fragment can encode an extra-membrane region, and the 3' end of the first nucleic acid fragment can encode an intra-membrane region fused to the 5' end of the second nucleic acid fragment. In certain aspects the first nucleic acid

fragment of this type can encode, *e.g.*, a G-protein coupled receptor (GPCR). In certain aspects the GPCR can be the human frizzled-4 protein (FZD4), or a fragment thereof, and the polynucleotide can encode a polypeptide that includes amino acids 20 to 892 of SEQ ID NO: 2. In certain aspects the polypeptide can further include a signal peptide, *e.g.*, amino acids 1 to 19 of SEQ ID NO: 2. In certain aspects the GPCR can be a CXC chemokine receptor, *e.g.*, CXCR4, or a fragment thereof, and the polynucleotide can encode a polypeptide that includes the amino acid sequence SEQ ID NO: 3.

[0006] In certain aspects the multi-pass IMP can have an even number of transmembrane domains, and both the 5' and 3' ends of the first nucleic acid fragment can encode intra-membrane regions. In certain aspects, the second nucleic acid fragment can be fused to 3' end of the first nucleic acid fragment. In certain aspects the IMP can be, *e.g.*, human CD20 protein, or a fragment thereof, and the polynucleotide can encode a polypeptide that includes the amino acid sequence SEQ ID NO: 4.

[0007] In certain aspects, the first and second nucleic acid fragments of a polynucleotide provided herein can be directly fused. In certain aspects the polynucleotide as provided herein can include a third nucleic acid fragment encoding a heterologous peptide, *e.g.*, a linker sequence, an amino acid tag or label, or a peptide or polypeptide sequence that facilitates purification, such as a histidine tag. In certain aspects a polynucleotide as provided here can be operably associated with a poxvirus promoter, *e.g.*, a p7.5, a T7, or H5 promoter.

[0008] The disclosure further provides an F13L fusion protein encoded by a polynucleotide as provided herein. The disclosure further provides a poxvirus genome, *e.g.*, a vaccinia virus genome, that includes a polynucleotide as provided herein. The disclosure further provides a recombinant vaccinia virus EEV that includes a poxvirus genome as provided herein.

[0009] The disclosure further provides a method of producing a recombinant vaccinia virus EEV as provided herein where the method includes infecting a host cell permissive for vaccinia virus infectivity with a vaccinia virus comprising a poxvirus genome as provided herein, and recovering EEV released from the host cell.

[0010] The disclosure further provides a method to display an integral membrane protein (IMP) or fragment thereof in a native conformation where the method includes infecting host cells permissive for poxvirus infectivity with a recombinant poxvirus that expresses an IMP or fragment thereof as a fusion protein with poxvirus EEV-specific protein or membrane-associated fragment thereof, where EEV produced by the infected host cell comprise the

IMP fusion protein as part of the EEV outer envelope membrane and recovering EEV released from the host cell. In certain aspects the IMP or fragment thereof displays on the surface of the EEV in a native conformation. In certain aspects the EEV-specific protein can be the vaccinia virus A33R protein, A34R protein, A56R protein, B5R protein, A36R protein, F13L protein, any membrane-associated fragment thereof, or any combination thereof.

[0011] In certain aspects the EEV-specific protein is F13L (SEQ ID NO: 1) or a functional fragment thereof. In certain aspects the IMP is a multi-pass membrane protein that includes at least two, at least three, at least four, at least five, at least six or at least seven transmembrane domains. In certain aspects the IMP can be a G-protein coupled receptor (GPCR), e.g., human FZD4 or CXCR4 as described above, that includes seven transmembrane domains, and the F13L protein can be fused to the C-terminus of the IMP. In certain aspects the IMP or fragment thereof can have an even number of transmembrane domains, e.g., human CD20 as described above, where both the N-terminus and the C-terminus of the IMP or fragment thereof are intra-membrane, and the F13L can be fused to the N-terminus or the C-terminus of the IMP.

[0012] In certain aspects the membrane-associated EEV specific protein fragment can include or consist of the stalk, transmembrane, and intra-membrane domains of the vaccinia virus A56R protein, e.g., amino acids 108 to 314 of SEQ ID NO: 5. In certain aspects IMP portion of the A56R fusion protein can include the extracellular domain of human FZD4, e.g., the fusion protein can include amino acids 20 to 370 of SEQ ID NO: 6, the extracellular domain of human ErbB2 (Her2), e.g., the fusion protein can include amino acids 20 to 855 of SEQ ID NO: 7, or the extracellular domain of human CD100 (Semaphorin 4D), e.g., the fusion protein can include amino acids 20 to 935 of SEQ ID NO: 8.

[0013] In certain aspects the membrane-associated EEV specific protein fragment can include or consist of the transmembrane and intra-membrane domains, or the stalk, transmembrane, and intra-membrane domains of the vaccinia virus B5R protein, e.g., amino acids 276 to 317 of SEQ ID NO: 9 or amino acids 238 to 317 of SEQ ID NO: 9, respectively. In certain aspects the IMP portion of the B5R fusion protein can include the extracellular domain of human FZD4, e.g., the fusion protein can includes amino acids 20 to 243 of SEQ ID NO: 10 or amino acids 20 to 281 of SEQ ID NO: 11.

[0014] The disclosure further provides a fusion protein comprising: amino acids 20 to 892 of SEQ ID NO: 2; SEQ ID NO: 3; SEQ ID NO: 4; amino acids 20 to 370 of SEQ ID NO: 6; amino acids 20 to 855 of SEQ ID NO: 7; amino acids 20 to 935 of SEQ ID NO: 8; amino acids 20 to 243 of SEQ ID NO: 10; amino acids 20 to 281 of SEQ ID NO: 11, amino acids 20 to 506 of SEQ ID NO: 13, or amino acids 20 to 235 of SEQ ID NO: 14. A fusion protein as provided, when expressed by a recombinant poxvirus, e.g., a vaccinia virus, can appear on the surface of a poxvirus extracellular enveloped virion (EEV) in a native conformation. A recombinant poxvirus EEV comprising the fusion protein is also provided. The disclosure further provides a recombinant poxvirus EEV that includes a heterologous IMP or fragment thereof fused to a poxvirus EEV-specific protein or membrane-associated fragment thereof, where the fusion protein is situated in the EEV outer envelope membrane, and where the IMP or fragment thereof displays on the surface of the EEV in its native conformation. In certain aspects the recombinant poxvirus EEV is a vaccinia virus EEV.

[0015] The disclosure further provides a method to select antibodies that bind to a multi-pass membrane protein where the method includes attaching recombinant EEV as provided herein to a solid support; providing an antibody display library, where the library comprises display packages displaying a plurality of antigen binding domains; contacting the display library with the EEV such that display packages displaying antigen binding domains that specifically binds to the IMP expressed on the EEV can bind thereto; removing unbound display packages; and recovering display packages that display an antigen binding domain specific for the IMP expressed on the EEV. In certain aspects of this method the recombinant EEV are inactivated prior to attachment to the solid support, e.g., by incubation with Psoralen (Trioxsalen, 4'-aminomethyl-, hydrochloride) in the presence of UV irradiation. In certain aspects of this method the recombinant EEV are attached to the solid surface via reaction with tosyl groups attached to the surface. In certain aspects the solid surface can be tosyl-activated magnetic beads. In certain aspects of this method the recombinant EEV are biotinylated and attached to a streptavidin coated solid surface, e.g., streptavidin-coated magnetic beads.

BRIEF DESCRIPTION OF THE DRAWINGS/FIGURES

[0016] **FIGURE 1A-C:** Diagrammatic depiction of integral membrane proteins (IMPs) or fragment thereof fused to vaccinia virus extracellular enveloped virion (EEV)-specific

proteins or fragments thereof. The parallel horizontal lines are a diagram of the EEV outer membrane. **FIG. 1A** diagrams the extracellular domain (ECD) of an IMP fused to a fragment of the vaccinia A56R protein that includes the transmembrane domain and the intra-membrane domain. **FIG. 1B** diagrams the topology of a typical G protein-coupled receptor fused to the vaccinia virus EEV-specific F13L protein. F13L is associated with the inner side of the EEV outer membrane via palmitoylation. **FIG. 1C** diagrams the topology of an IMP with an even number of transmembrane domains, *e.g.*, CD20), fused to F13L.

- [0017] **FIGURE 2:** Demonstration of incorporation of CD20-F13L and CD20 ECD-A56R fusion proteins into vaccinia virus EEV particles.
- [0018] **FIGURE 3A:** Demonstration of preferential incorporation of CD20-F13L fusion protein over untagged CD20 into vaccinia virus EEV particles.
- [0019] **FIGURE 3B:** Demonstration of preferential incorporation of FZD4-F13L fusion protein over untagged (unfused) FZD4 into vaccinia virus EEV particles.
- [0020] **FIGURE 4:** Incorporation of additional IMP-EEV protein fusions into vaccinia virus EEV. “CD20” is a CD20-F13L fusion protein, “CXCR4” is a CXCR4-F13L fusion protein, “Her2” is a Her2 ECD-A56R fusion protein; and “CD100” is a CD100 ECD-A56R fusion protein.
- [0021] **FIGURE 5:** Outline of assay for screening an antibody display library for display packages that bind to an IMP of interest expressed on vaccinia virus EEV.
- [0022] **FIGURE 6A:** Binding of vaccinia virus EEV expressing an anti-HER-2 antibody to vaccinia virus EEV expressing the HER2 ECD as a fusion with the vaccinia virus A56R protein, bound by tosyl-groups to magnetic beads.
- [0023] **FIGURE 6B:** Binding of vaccinia virus EEV expressing an anti-FZD antibody to vaccinia virus EEV expressing FZD4 as a fusion with the vaccinia virus F13L protein, bound by tosyl-groups to magnetic beads.
- [0024] **FIGURE 6C:** Binding of vaccinia virus EEV expressing an anti-CXCR4 antibody to vaccinia virus EEV expressing the CXCR4 as a fusion with the vaccinia virus F13L protein, bound by tosyl-groups to magnetic beads.
- [0025] **FIGURE 6D:** Binding of vaccinia virus EEV expressing an anti-CD100 (“sema”) antibody to vaccinia virus EEV expressing the CD100 ECD as a fusion with the vaccinia virus A56R protein, bound by tosyl-groups to magnetic beads.

- [0026] **FIGURE 7:** FACS scans showing enrichment for anti FZD4 antibodies following panning on inactivated FZD-ECD-A45R-expressing EEV bound by tosyl-groups to magnetic beads after 3 (Rd3), 4 (Rd4), and 5 (Rd5) rounds of panning. The top row shows antibody-expressing virus-infected cells stained with 10 µg/ml FZD-His, followed by anti-His-Dyelight650 and anti-Fab-FITC. The bottom row shows antibody-expressing virus-infected cells stained with 10 µg/ml CD100-His (negative control), followed by anti-His-Dyelight650 and anti-Fab-FITC.
- [0027] **FIGURE 8:** Incorporation two different protein fusions (HA-A56R fusion and FZD4-F13L fusion) into vaccinia virus EEV. EEV expressing the HA-A56R fusion alone, the FZD4-F13L fusion alone, or both fusion proteins, were tested for binding to either anti-FZD4-coated beads or anti-HA coated beads.
- [0028] **FIGURE 9:** Specific recovery of anti-CXCR4-expressing EEV by magnetic beads coated with EEV expressing both an HA-A56R fusion and CXCR4-F13L fusion. The antigen-EEV were coupled to anti-HA coated beads.
- [0029] **FIGURE 10:** Binding of biotinylated vaccinia virus EEV expressing the designated fusion proteins to streptavidin coated magnetic beads.

DETAILED DESCRIPTION

- [0030] This disclosure provides methods and compositions for expressing and displaying integral membrane proteins (IMPs), *e.g.*, multi-pass (IMPs), in a conformationally intact or native state on the surface of extracellular enveloped virion particles (EEV) of poxviruses, *e.g.*, vaccinia virus, as a fusion with a polypeptide segment an EEV-specific membrane-associated protein, *e.g.*, F13L.

Definitions

- [0031] The term "a" or "an" entity refers to one or more of that entity; for example, "a binding molecule," is understood to represent one or more binding molecules. As such, the terms "a" (or "an"), "one or more," and "at least one" can be used interchangeably herein.
- [0032] Furthermore, "and/or" where used herein is to be taken as specific disclosure of each of the two specified features or components with or without the other. Thus, the term and/or" as used in a phrase such as "A and/or B" herein is intended to include "A and B," "A or B," "A" (alone), and "B" (alone). Likewise, the term "and/or" as used in a phrase such as "A, B,

and/or C" is intended to encompass each of the following embodiments: A, B, and C; A, B, or C; A or C; A or B; B or C; A and C; A and B; B and C; A (alone); B (alone); and C (alone).

[0033] Unless defined otherwise, technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure is related. For example, the Concise Dictionary of Biomedicine and Molecular Biology, Juo, Pei-Show, 2nd ed., 2002, CRC Press; The Dictionary of Cell and Molecular Biology, 3rd ed., 1999, Academic Press; and the Oxford Dictionary Of Biochemistry And Molecular Biology, Revised, 2000, Oxford University Press, provide one of skill with a general dictionary of many of the terms used in this disclosure.

[0034] Units, prefixes, and symbols are denoted in their Système International de Unites (SI) accepted form. Numeric ranges are inclusive of the numbers defining the range. Unless otherwise indicated, amino acid sequences are written left to right in amino to carboxy orientation. The headings provided herein are not limitations of the various aspects or aspects of the disclosure, which can be had by reference to the specification as a whole. Accordingly, the terms defined immediately below are more fully defined by reference to the specification in its entirety.

[0035] As used herein, the term "non-naturally occurring" substance, composition, entity, and/or any combination of substances, compositions, or entities, or any grammatical variants thereof, is a conditional term that explicitly excludes, but only excludes, those forms of the substance, composition, entity, and/or any combination of substances, compositions, or entities that are well-understood by persons of ordinary skill in the art as being "naturally-occurring," or that are, or might be at any time, determined or interpreted by a judge or an administrative or judicial body to be, "naturally-occurring."

[0036] As used herein, the term "polypeptide" is intended to encompass a singular "polypeptide" as well as plural "polypeptides," and refers to a molecule composed of monomers (amino acids) linearly linked by amide bonds (also known as peptide bonds). The term "polypeptide" refers to any chain or chains of two or more amino acids, and does not refer to a specific length of the product. Thus, peptides, dipeptides, tripeptides, oligopeptides, "protein," "amino acid chain," or any other term used to refer to a chain or chains of two or more amino acids are included within the definition of "polypeptide," and the term "polypeptide" can be used instead of, or interchangeably with any of these terms.

The term "polypeptide" is also intended to refer to the products of post-expression modifications of the polypeptide, including without limitation glycosylation, acetylation, phosphorylation, amidation, and derivatization by known protecting/blocking groups, proteolytic cleavage, or modification by non-naturally occurring amino acids. A polypeptide can be derived from a biological source or produced by recombinant technology, but is not necessarily translated from a designated nucleic acid sequence. It can be generated in any manner, including by chemical synthesis.

[0037] A polypeptide as disclosed herein can be of a size of about 3 or more, 5 or more, 10 or more, 20 or more, 25 or more, 50 or more, 75 or more, 100 or more, 200 or more, 500 or more, 1,000 or more, or 2,000 or more amino acids. Polypeptides can have a defined three-dimensional structure, although they do not necessarily have such structure. Polypeptides with a defined three-dimensional structure are referred to as folded, and polypeptides that do not possess a defined three-dimensional structure, but rather can adopt a large number of different conformations, and are referred to as unfolded. As used herein, the term glycoprotein refers to a *protein* coupled to at least one carbohydrate moiety that is attached to the protein via an oxygen-containing or a nitrogen-containing side chain of an amino acid, *e.g.*, a serine or an asparagine.

[0038] By an "isolated" polypeptide or a fragment, variant, or derivative thereof is intended a polypeptide that is not in its natural milieu. No particular level of purification is required. For example, an isolated polypeptide can be removed from its native or natural environment. Recombinantly produced polypeptides and proteins expressed in host cells are considered isolated as disclosed herein, as are native or recombinant polypeptides that have been separated, fractionated, or partially or substantially purified by any suitable technique.

[0039] As used herein, the term "non-naturally occurring" polypeptide, or any grammatical variants thereof, is a conditional term that explicitly excludes, but only excludes, those forms of the polypeptide that are well-understood by persons of ordinary skill in the art as being "naturally-occurring," or that are, or might be at any time, determined or interpreted by a judge or an administrative or judicial body to be, "naturally-occurring."

[0040] Other polypeptides disclosed herein are fragments, derivatives, analogs, or variants of the foregoing polypeptides, and any combination thereof. The terms "fragment," "variant," "derivative" and "analog" as disclosed herein include any polypeptides that retain at least some of the properties of the corresponding native antibody or polypeptide, for example,

specifically binding to an antigen. Fragments of polypeptides include, for example, proteolytic fragments, as well as deletion fragments, in addition to specific antibody fragments discussed elsewhere herein. Variants of, *e.g.*, a polypeptide include fragments as described above, and also polypeptides with altered amino acid sequences due to amino acid substitutions, deletions, or insertions. In certain aspects, variants can be non-naturally occurring. Non-naturally occurring variants can be produced using art-known mutagenesis techniques. Variant polypeptides can comprise conservative or non-conservative amino acid substitutions, deletions or additions. Derivatives are polypeptides that have been altered so as to exhibit additional features not found on the original polypeptide. Examples include fusion proteins. Variant polypeptides can also be referred to herein as "polypeptide analogs." As used herein a "derivative" of a polypeptide can also refer to a subject polypeptide having one or more amino acids chemically derivatized by reaction of a functional side group. Also included as "derivatives" are those peptides that contain one or more derivatives of the twenty standard amino acids. For example, 4-hydroxyproline can be substituted for proline; 5-hydroxylysine can be substituted for lysine; 3-methylhistidine can be substituted for histidine; homoserine can be substituted for serine; and ornithine can be substituted for lysine.

[0041] A "conservative amino acid substitution" is one in which one amino acid is replaced with another amino acid having a similar side chain. Families of amino acids having similar side chains have been defined in the art, including basic side chains (*e.g.*, lysine, arginine, histidine), acidic side chains (*e.g.*, aspartic acid, glutamic acid), uncharged polar side chains (*e.g.*, asparagine, glutamine, serine, threonine, tyrosine, cysteine), nonpolar side chains (*e.g.*, glycine, alanine, valine, leucine, isoleucine, proline, phenylalanine, methionine, tryptophan), beta-branched side chains (*e.g.*, threonine, valine, isoleucine) and aromatic side chains (*e.g.*, tyrosine, phenylalanine, tryptophan, histidine). For example, substitution of a phenylalanine for a tyrosine is a conservative substitution. In certain embodiments, conservative substitutions in the sequences of the polypeptides and antibodies of the present disclosure do not abrogate the binding of the polypeptide or antibody containing the amino acid sequence, to the antigen to which the binding molecule binds. Methods of identifying nucleotide and amino acid conservative substitutions that do not eliminate antigen binding are well-known in the art (see, *e.g.*, Brummell *et al.*, *Biochem.* 32:1180-1 187 (1993); Kobayashi *et al.*,

Protein Eng. 12(10):879-884 (1999); and Burks *et al.*, *Proc. Natl. Acad. Sci. USA* 94:412-417 (1997)).

- [0042]** As used herein the term “integral membrane protein” or “IMP” refers to a protein or polypeptide that is attached to a biological membrane. One example of an IMP is a transmembrane protein, which spans the lipid bilayer of the biological membrane one or more times. Single-pass membrane proteins cross the membrane only once, while multi-pass membrane proteins weave in and out, crossing several times. Type I single-pass proteins are positioned with their amino terminus on the outer side of the membrane or “extra-membrane” and their carboxyl-terminus on the interior side of the membrane, or “intra-membrane.” Type II single-pass proteins have their amino-terminus on the intra-membrane side. Multi-pass transmembrane proteins pass through the membrane two or more times and can have a variety of different topologies. Those proteins with an even number of transmembrane domains will have both their amino terminus and carboxy terminus on the same side of the membrane. One example of such a protein is CD20, which is expressed on B cells. Those with an odd number of transmembrane domains will have their amino- and carboxy termini on opposite sides of the membrane. Examples include G-protein coupled receptors, which typically have 7 transmembrane domains, with the amino terminus on the extra-membrane side and the carboxy terminus on the intra-membrane side. Certain IMPs do not have transmembrane domains and are instead anchored to the membrane, *e.g.*, via a lipid such as glycosylphosphatidylinositol or palmitoyl group. IMPs have myriad biological functions including, but not limited to transporters, linkers, channels, receptors, enzymes, energy transduction or cell adhesion.
- [0043]** The term “polynucleotide” is intended to encompass a singular nucleic acid as well as plural nucleic acids, and refers to an isolated nucleic acid molecule or construct, *e.g.*, messenger RNA (mRNA), cDNA, or plasmid DNA (pDNA). A polynucleotide can comprise a conventional phosphodiester bond or a non-conventional bond (*e.g.*, an amide bond, such as found in peptide nucleic acids (PNA)). The terms “nucleic acid” or “nucleic acid sequence” refer to any one or more nucleic acid segments, *e.g.*, DNA or RNA fragments, present in a polynucleotide.
- [0044]** By an “isolated” nucleic acid or polynucleotide is intended any form of the nucleic acid or polynucleotide that is separated from its native environment. For example, gel-purified polynucleotide, or a recombinant polynucleotide encoding a polypeptide contained

in a vector would be considered to be “isolated.” Also, a polynucleotide segment, *e.g.*, a PCR product, that has been engineered to have restriction sites for cloning is considered to be “isolated.” Further examples of an isolated polynucleotide include recombinant polynucleotides maintained in heterologous host cells or purified (partially or substantially) polynucleotides in a non-native solution such as a buffer or saline. Isolated RNA molecules include *in vivo* or *in vitro* RNA transcripts of polynucleotides, where the transcript is not one that would be found in nature. Isolated polynucleotides or nucleic acids further include such molecules produced synthetically. In addition, polynucleotide or a nucleic acid can be or can include a regulatory element such as a promoter, ribosome binding site, or a transcription terminator.

[0045] As used herein, a “non-naturally occurring” polynucleotide, or any grammatical variants thereof, is a conditional definition that explicitly excludes, but only excludes, those forms of the polynucleotide that are well-understood by persons of ordinary skill in the art as being “naturally-occurring,” or that are, or that might be at any time, determined or interpreted by a judge or an administrative or judicial body to be, “naturally-occurring.”

[0046] As used herein, a “coding region” is a portion of nucleic acid that consists of codons translated into amino acids. Although a “stop codon” (TAG, TGA, or TAA) is not translated into an amino acid, it can be considered to be part of a coding region, but any flanking sequences, for example promoters, ribosome binding sites, transcriptional terminators, introns, and the like, are not part of a coding region. Two or more coding regions can be present in a single polynucleotide construct, *e.g.*, on a single vector, or in separate polynucleotide constructs, *e.g.*, on separate (different) vectors. Furthermore, any vector can contain a single coding region, or can comprise two or more coding regions, *e.g.*, a single vector can separately encode an immunoglobulin heavy chain variable region and an immunoglobulin light chain variable region. In addition, a vector, polynucleotide, or nucleic acid can include heterologous coding regions, either fused or unfused to another coding region. Heterologous coding regions include without limitation, those encoding specialized elements or motifs, such as a secretory signal peptide or a heterologous functional domain.

[0047] In certain embodiments, the polynucleotide or nucleic acid is DNA. In the case of DNA, a polynucleotide comprising a nucleic acid that encodes a polypeptide normally can include a promoter and/or other transcription or translation control elements operably associated with one or more coding regions. An operable association is when a coding region

for a gene product, *e.g.*, a polypeptide, is associated with one or more regulatory sequences in such a way as to place expression of the gene product under the influence or control of the regulatory sequence(s). Two DNA fragments (such as a polypeptide coding region and a promoter associated therewith) are "operably associated" if induction of promoter function results in the transcription of mRNA encoding the desired gene product and if the nature of the linkage between the two DNA fragments does not interfere with the ability of the expression regulatory sequences to direct the expression of the gene product or interfere with the ability of the DNA template to be transcribed. Thus, a promoter region would be operably associated with a nucleic acid encoding a polypeptide if the promoter was capable of effecting transcription of that nucleic acid. The promoter can be a cell-specific promoter that directs substantial transcription of the DNA in predetermined cells. Other transcription control elements, besides a promoter, for example enhancers, operators, repressors, and transcription termination signals, can be operably associated with the polynucleotide to direct cell-specific transcription.

[0048] A variety of transcription control regions are known to those skilled in the art. These include, without limitation, transcription control regions that function in vertebrate cells, such as, but not limited to, promoter and enhancer segments from cytomegaloviruses (the immediate early promoter, in conjunction with intron-A), simian virus 40 (the early promoter), and retroviruses (such as Rous sarcoma virus). Other transcription control regions include those derived from vertebrate genes such as actin, heat shock protein, bovine growth hormone and rabbit β -globin, as well as other sequences capable of controlling gene expression in eukaryotic cells. Additional suitable transcription control regions include tissue-specific promoters and enhancers as well as lymphokine-inducible promoters (*e.g.*, promoters inducible by interferons or interleukins).

[0049] Poxvirus promoters (*e.g.* p7.5 or H5) or the bacteriophage T7 promoter can also be used as transcription control regions. When employing a T7 promoter, an inducible vaccinia expression system can be utilized. The vaccinia expression system can include, but is not limited, to a first recombinant vaccinia virus that encodes the entire bacteriophage T7 gene 1 coding region for T7 RNA polymerase, and a second recombinant vaccinia virus that encodes a gene of interest flanked by a T7 promoter and termination regulatory elements. Dual infection of eukaryotic cells with both recombinant vaccinia viruses results in synthesis

of the T7 RNA polymerase and expression of the gene of interest controlled by the T7 promoter.

[0050] Similarly, a variety of translation control elements are known to those of ordinary skill in the art. These include, but are not limited to ribosome binding sites, translation initiation and termination codons, and elements derived from picornaviruses (particularly an internal ribosome entry site, or IRES, also referred to as a CITE sequence).

[0051] In other embodiments, a polynucleotide can be RNA, for example, in the form of messenger RNA (mRNA), transfer RNA, or ribosomal RNA.

[0052] Polynucleotide and nucleic acid coding regions can be associated with additional coding regions that encode secretory or signal peptides, which direct the secretion of a polypeptide encoded by a polynucleotide as disclosed herein. According to the signal hypothesis, proteins secreted by mammalian cells have a signal peptide or secretory leader sequence that is cleaved from the mature protein once export of the growing protein chain across the rough endoplasmic reticulum has been initiated. Those of ordinary skill in the art are aware that polypeptides secreted by vertebrate cells can have a signal peptide fused to the N-terminus of the polypeptide, which is cleaved from the complete or "full length" polypeptide to produce a secreted or "mature" form of the polypeptide. In certain embodiments, the native signal peptide, *e.g.*, an immunoglobulin heavy chain or light chain signal peptide is used, or a functional derivative of that sequence that retains the ability to direct the secretion of the polypeptide that is operably associated with it. Alternatively, a heterologous mammalian signal peptide, or a functional derivative thereof, can be used. For example, the wild-type leader sequence can be substituted with the leader sequence of human tissue plasminogen activator (TPA) or mouse β -glucuronidase.

[0053] As used herein, a "library" is a representative genus of polynucleotides, *e.g.*, a group of polynucleotides related through, for example, their origin from a single animal species, tissue type, organ, or cell type, where the library collectively comprises at least two different species within a given genus of polynucleotides. A library of polynucleotides can include, *e.g.*, at least two, at least 5, at least 10, 100, 10^3 , 10^4 , 10^5 , 10^6 , 10^7 , 10^8 , or 10^9 different species within a given genus of polynucleotides. In certain aspects, a library of polynucleotides as provided herein can encode a plurality of polypeptides that contains a polypeptide of interest. In certain aspects, a library of polynucleotides as provided herein can encode a plurality of immunoglobulin subunit polypeptides, *e.g.*, heavy chain subunit

polypeptides or light chain subunit polypeptides. In this context, a “library” as provided herein comprises polynucleotides of a common genus, the genus being polynucleotides encoding immunoglobulin subunit polypeptides of a certain type and class *e.g.*, a library might encode a human μ , γ -1, γ -2, γ -3, γ -4, α -1, α -2, ϵ , or δ heavy chain, or a human κ or λ light chain. Although each member of any one library constructed according to the methods provided herein can encode the same heavy or light chain constant region and/or a membrane anchoring domain, the library can collectively comprise at least two, at least 5, or at least 10, 100, 10^3 , 10^4 , 10^5 , 10^6 , 10^7 , 10^8 , or 10^9 different variable region associated with the common constant region.

[0054] In other embodiments, the library can a plurality of immunoglobulin single-chain fragments that comprise a variable region, such as a light chain variable region or a heavy chain variable region, and/or both a light chain variable region and a heavy chain variable region, *e.g.*, an ScFv fragment.

[0055] As used herein, a “display library” is a library of polynucleotides each carried in a “display package” that expresses the polypeptide encoded by the library polynucleotide on its surface. An antibody display library, for example, can include plurality of display packages, each displaying an antigen binding domain of an antibody on its surface. When the display library is permitted to interact with an antigen of interest, *e.g.*, immobilized on a solid surface, those display packages that bind the antigen can be isolated from the rest of the library and recovered. The polynucleotide encoding the antigen binding domain displayed on the surface of the display package can then be isolated. Display libraries include, without limitation, phage display libraries in bacteria or libraries in eukaryotic systems, *e.g.*, yeast display, retroviral display, or expression in DNA viruses such as poxviruses. See, *e.g.*, U.S. Patent No. 7,858,559, and U.S. Patent Appl. Publication No. 2013-028892, which are incorporated herein by reference in their entireties. In certain aspects, an antibody display library can be prepared in a poxvirus, *e.g.*, vaccinia virus vector, as fusion proteins with an EEV-specific protein, such that the “display packages” are EEV particles. See U.S. Patent Appl. Publication No. 2013-028892.

[0056] Such display libraries can be screened against the IMP fusion proteins displayed on the surface of EEV as provided herein.

[0057] By “recipient cell” or “host cell” or “cell” is meant a cell or population of cells in which a recombinant protein can be expressed, a virus can be propagated, or polynucleotide

libraries as provided herein can be constructed and/or propagated. A host cell as provided herein is typically a eukaryotic cell or cell line, *e.g.*, a vertebrate, mammalian, rodent, mouse, primate, or human cell or cell line. By “a population of host cells” is meant a group of cultured cells which a “library” as provided herein can be constructed, propagated, and/or expressed. Any host cell which is permissive for vaccinia virus infectivity is suitable for the methods provided by this disclosure. Host cells for use in the methods provided herein can be adherent, *e.g.*, host cells that grow attached to a solid substrate, or, alternatively, the host cells can be in suspension.

[0058] Host cells as provided herein can comprise a constitutive secretory pathway, where proteins, *e.g.*, proteins of interest expressed by the cell or by a library, are secreted from the interior of the cell either to be expressed on a cell or viral membrane surface or to be fully secreted as soluble polypeptides. In certain aspects, proteins of interest expressed on or in a biological membrane, *e.g.*, an IMP, are expressed on the surface of an enveloped virus produced by the host cell, *e.g.*, an extracellular enveloped vaccinia virus, or EEV. IMPs can follow the same pathway as fully secreted forms or proteins, passing through to the ER lumen, except that they can be retained in the ER membrane by the presence of one or more stop-transfer signals, or “transmembrane domains.” Transmembrane domains are hydrophobic stretches of about 20 amino acids that adopt an alpha-helical conformation as they transverse the membrane. Membrane embedded proteins are anchored in the phospholipid bilayer of the plasma membrane. Transmembrane forms of polypeptides of interest, *e.g.*, membrane-anchored immunoglobulin heavy chain polypeptides typically utilize amino terminal signal peptides as do fully secreted forms.

[0059] Signal peptides, transmembrane domains, and cytosolic or “intra-membrane” domains are known for a wide variety of membrane bound and/or fully secreted proteins.

[0060] Suitable transmembrane domains can include, but are not limited to the TM domain of the vaccinia virus EEV-specific HA protein A56R, or the EEV-specific vaccinia virus transmembrane proteins A33R, A34R, A36R, or B5R. See, *e.g.*, U.S. Patent Appl. Publ. No. 2013/0288927, published October 31, 2013, and incorporated herein by reference in its entirety. In certain aspects the EEV specific protein can be anchored to the inner surface of the viral envelope via a palmitoyl group, *e.g.*, the vaccinia virus protein F13L, discussed in more detail elsewhere herein.

- [0061] As used herein, the term “binding molecule” refers in its broadest sense to a molecule that specifically binds to a receptor, *e.g.*, an epitope or an antigenic determinant. As described further herein, a binding molecule can comprise one or more “antigen binding domains” described herein. A non-limiting example of a binding molecule is an antibody or fragment thereof that retains antigen-specific binding.
- [0062] The terms “binding domain” and “antigen binding domain” are used interchangeably herein and refer to a region of a binding molecule that is necessary and sufficient to specifically bind to an epitope. For example, an “Fv,” *e.g.*, a variable heavy chain and variable light chain of an antibody, either as two separate polypeptide subunits or as a single chain, is considered to be a “binding domain.”
- [0063] Other antigen binding domains include, without limitation, the variable heavy chain (VHH) of an antibody derived from a camelid species, or six immunoglobulin complementarity determining regions (CDRs) expressed in a fibronectin scaffold.
- [0064] The terms “antibody” and “immunoglobulin” can be used interchangeably herein. An antibody (or a fragment, variant, or derivative thereof as disclosed herein) includes at least the variable region of a heavy chain (*e.g.*, for camelid species) or at least the variable regions of a heavy chain and a light chain. Basic immunoglobulin structures in vertebrate systems are relatively well understood. *See, e.g.*, Harlow *et al.*, *Antibodies: A Laboratory Manual*, (Cold Spring Harbor Laboratory Press, 2nd ed. 1988). Unless otherwise stated, the term “antibody” encompasses anything ranging from a small antigen binding fragment of an antibody to a full sized antibody, *e.g.*, an IgG antibody that includes two complete heavy chains and two complete light chains.
- [0065] The term “immunoglobulin” comprises various broad classes of polypeptides that can be distinguished biochemically. Those skilled in the art will appreciate that heavy chains are classified as gamma, mu, alpha, delta, or epsilon, (γ , μ , α , δ , ϵ) with some subclasses among them (*e.g.*, $\gamma 1$ - $\gamma 4$ or $\alpha 1$ - $\alpha 2$). It is the nature of this chain that determines the “class” of the antibody as IgG, IgM, IgA, IgG, or IgE, respectively. The immunoglobulin subclasses (isotypes) *e.g.*, IgG₁, IgG₂, IgG₃, IgG₄, IgA₁, IgA₂, etc. are well characterized and are known to confer functional specialization.
- [0066] Light chains are classified as either kappa or lambda (κ , λ). Each heavy chain class can be bound with either a kappa or lambda light chain. In general, the light and heavy chains are covalently bonded to each other, and the “tail” portions of the two heavy chains

are bonded to each other by covalent disulfide linkages or non-covalent linkages when the immunoglobulins are generated either by hybridomas, B cells or genetically engineered host cells. In the heavy chain, the amino acid sequences run from an N-terminus at the forked ends of the Y configuration to the C-terminus at the bottom of each chain. The basic structure of certain antibodies, *e.g.*, IgG antibodies, includes two heavy chain subunits and two light chain subunits covalently connected via disulfide bonds to form a “Y” structure, also referred to herein as an “H2L2” structure.

[0067] The term “epitope” includes any molecular determinant capable of specific binding to an antibody. In certain aspects, an epitope can include chemically active surface groupings of molecules such as amino acids, sugar side chains, phosphoryl, or sulfonyl, and, in certain aspects, can have three dimensional structural characteristics, and or specific charge characteristics. An epitope is a region of a target that is bound by an antibody.

[0068] The term “target” is used in the broadest sense to include substances that can be bound by a binding molecule. A target can be, *e.g.*, a polypeptide, a nucleic acid, a carbohydrate, a lipid, or other molecule. Moreover, a “target” can, for example, be a cell, an organ, or an organism that comprises an epitope bound that can be bound by a binding molecule.

[0069] Both the light and heavy chains are divided into regions of structural and functional homology. The terms “constant” and “variable” are used functionally. In this regard, it will be appreciated that the variable regions (which can be called “variable domains” interchangeably herein) of both the variable light (VL) and variable heavy (VH) chain portions determine antigen recognition and specificity. Conversely, the constant domains of the light chain (CL) and the heavy chain (*e.g.*, CH1, CH2 or CH3) confer biological properties such as secretion, transplacental mobility, Fc receptor binding, complement binding, and the like. By convention the numbering of the constant region domains increases as they become more distal from the antigen binding site or amino-terminus of the antibody. The N-terminal portion is a variable region and at the C-terminal portion is a constant region; the CH3 (or CH4 in the case of IgM) and CL domains are at the carboxy-terminus of the heavy and light chain, respectively.

[0070] The six “complementarity determining regions” or “CDRs” present in an antibody antigen binding domain are short, non-contiguous sequences of amino acids that are specifically positioned to form the antigen binding domain as the antibody assumes its three

dimensional configuration in an aqueous environment. The remainder of the amino acids in the antigen binding domain, referred to as "framework" regions, show less inter-molecular variability. The framework regions largely adopt a β -sheet conformation and the CDRs form loops that connect, and in some cases form part of, the β -sheet structure. Thus, framework regions act to form a scaffold that provides for positioning the CDRs in correct orientation by inter-chain, non-covalent interactions. The antigen binding domain formed by the positioned CDRs defines a surface complementary to the epitope on the immunoreactive antigen. This complementary surface promotes the non-covalent binding of the antibody to its cognate epitope. The amino acids that make up the CDRs and the framework regions, respectively, can be readily identified for any given heavy or light chain variable region by one of ordinary skill in the art, since they have been defined in various different ways (*see*, "Sequences of Proteins of Immunological Interest," Kabat, E., *et al.*, U.S. Department of Health and Human Services, (1983); and Chothia and Lesk, *J. Mol. Biol.*, 196:901-917 (1987), which are incorporated herein by reference in their entireties).

[0071] In the case where there are two or more definitions of a term that is used and/or accepted within the art, the definition of the term as used herein is intended to include all such meanings unless explicitly stated to the contrary. A specific example is the use of the term "complementarity determining region" ("CDR") to describe the non-contiguous antigen combining sites found within the variable region of both heavy and light chain polypeptides. These particular regions have been described, for example, by Kabat *et al.*, U.S. Dept. of Health and Human Services, "Sequences of Proteins of Immunological Interest" (1983) and by Chothia *et al.*, *J. Mol. Biol.* 196:901-917 (1987), which are incorporated herein by reference. Immunoglobulin variable domains can also be analyzed, *e.g.*, using the IMGT information system ([www://imgt.cines.fr/](http://imgt.cines.fr/)) (IMGT®/V-Quest) to identify variable region segments, including CDRs. (*See, e.g.*, Brochet *et al.*, *Nucl. Acids Res.*, 36:W503-508, 2008).

[0072] Kabat *et al.* also defined a numbering system for variable domain sequences that is applicable to any antibody. One of ordinary skill in the art can unambiguously assign this system of "Kabat numbering" to any variable domain sequence, without reliance on any experimental data beyond the sequence itself. As used herein, "Kabat numbering" refers to the numbering system set forth by Kabat *et al.*, U.S. Dept. of Health and Human Services, "Sequence of Proteins of Immunological Interest" (1983). Unless use of the Kabat

numbering system is explicitly noted, however, consecutive numbering is used for all amino acid sequences in this disclosure.

[0073] Binding molecules, *e.g.*, antibodies or antigen binding fragments, variants, or derivatives thereof include, but are not limited to, polyclonal, monoclonal, human, humanized, or chimeric antibodies, single chain antibodies, epitope-binding fragments, *e.g.*, Fab, Fab' and F(ab')₂, Fd, Fvs, single-chain Fvs (scFv), single-chain antibodies, disulfide-linked Fvs (sdFv), single domain antibodies such as camelid VHH antibodies, fragments comprising either a VL or VH domain, fragments produced by a Fab expression library. ScFv molecules are known in the art and are described, *e.g.*, in US patent 5,892,019. Immunoglobulin or antibody molecules encompassed by this disclosure can be of any type (*e.g.*, IgG, IgE, IgM, IgD, IgA, and IgY), class (*e.g.*, IgG1, IgG2, IgG3, IgG4, IgA1 and IgA2) or subclass of immunoglobulin molecule. Also contemplated are immunoglobulin new antigen receptor (IgNAR) isotypes that are bivalent and comprise a single chain that includes an IgNAR variable domain (VNAR). (*See*, Walsh *et al.*, *Virology* 411:132-141, 2011).

[0074] By "specifically binds," it is generally meant that a binding molecule, *e.g.*, an antibody or fragment, variant, or derivative thereof binds to an epitope via its antigen binding domain, and that the binding entails some complementarity between the antigen binding domain and the epitope. According to this definition, a binding molecule is said to "specifically bind" to an epitope when it binds to that epitope, via its antigen binding domain more readily than it would bind to a random, unrelated epitope. The term "specificity" is used herein to qualify the relative affinity by which a certain binding molecule binds to a certain epitope. For example, binding molecule "A" can be deemed to have a higher specificity for a given epitope than binding molecule "B," or binding molecule "A" can be said to bind to epitope "C" with a higher specificity than it has for related epitope "D."

[0075] As used herein, the term "affinity" refers to a measure of the strength of the binding of an individual epitope with one or more antigen binding domains, *e.g.*, of an immunoglobulin molecule. *See, e.g.*, Harlow *et al.*, *Antibodies: A Laboratory Manual*, (Cold Spring Harbor Laboratory Press, 2nd ed. 1988) at pages 27-28. As used herein, the term "avidity" refers to the overall stability of the complex between a population of antigen binding domains and an antigen. *See, e.g.*, Harlow at pages 29-34. Avidity is related to both the affinity of individual antigen binding domains in the population with specific epitopes, and also the valencies of the immunoglobulins and the antigen. For example, the interaction

between a bivalent monoclonal antibody and an antigen with a highly repeating epitope structure, such as a polymer, would be one of high avidity. An interaction between a bivalent monoclonal antibody with a receptor present at a high density on a cell surface would also be of high avidity.

[0076] As used herein, the term "heavy chain subunit" or "heavy chain domain" includes amino acid sequences derived from an immunoglobulin heavy chain, a binding molecule, *e.g.*, an antibody comprising a heavy chain subunit can include at least one of: a VH domain, a CH1 domain, a hinge (*e.g.*, upper, middle, and/or lower hinge region) domain, a CH2 domain, a CH3 domain, a CH4 domain, or a variant or fragment thereof.

[0077] As used herein, the term "light chain subunit" or "light chain domain" includes amino acid sequences derived from an immunoglobulin light chain. The light chain subunit includes at least one of a VL or CL (*e.g.*, C κ or C λ) domain.

[0078] Binding molecules, *e.g.*, antibodies or antigen binding fragments, variants, or derivatives thereof can be described or specified in terms of the epitope(s) or portion(s) of an antigen that they recognize or specifically bind. The portion of a target antigen that specifically interacts with the antigen binding domain of an antibody is an "epitope," or an "antigenic determinant." A target antigen can comprise a single epitope or at least two epitopes, and can include any number of epitopes, depending on the size, conformation, and type of antigen.

[0079] As used herein, the terms "linked," "fused" or "fusion" or other grammatical equivalents can be used interchangeably. These terms refer to the joining together of two more elements or components, by whatever means including chemical conjugation or recombinant means. An "in-frame fusion" refers to the joining of two or more polynucleotide open reading frames (ORFs) to form a continuous longer ORF, in a manner that maintains the translational reading frame of the original ORFs. Thus, a recombinant fusion protein is a single protein containing two or more segments that correspond to polypeptides encoded by the original ORFs (which segments are not normally so joined in nature). Although the reading frame is thus made continuous throughout the fused segments, the segments can be physically or spatially separated by, for example, in-frame linker sequence. For example, polynucleotides encoding an IMP and a vaccinia virus EEV-specific protein can be fused, in-frame, but be separated by a polynucleotide encoding a linker or spacer, as long as the "fused" open reading frames are co-translated as part of a continuous polypeptide.

[0080] As used herein, the term “hemagglutinin tag” or “HA tag” is a protein derived from a human influenza hemagglutinin surface glycoprotein (HA) corresponding to amino acids 98-106. The HA tag is extensively used as a general epitope tag in expression vectors. Recombinant proteins can be engineered to express the HA tag, which does not appear to interfere with the bioactivity or the biodistribution of the recombinant protein. This tag facilitates the detection, isolation, and purification of the protein of interest.

[0081] In the context of polypeptides, a "linear sequence" or a "sequence" is an order of amino acids in a polypeptide from the amino or N-terminus to the carboxyl or C-terminus, in which amino acids that neighbor each other in the sequence are contiguous in the primary structure of the polypeptide.

[0082] A portion of a polypeptide that is “amino-terminal” or “N-terminal” to another portion of a polypeptide is that portion that comes earlier in the sequential polypeptide chain. Similarly a portion of a polypeptide that is “carboxy-terminal” or “C-terminal” to another portion of a polypeptide is that portion that comes later in the sequential polypeptide chain.

[0083] The term “expression” as used herein refers to a process by which a gene produces a biochemical, for example, a polypeptide. The process includes any manifestation of the functional presence of the gene within the cell including, without limitation, gene knockdown as well as both transient expression and stable expression. It includes without limitation transcription of the gene into messenger RNA (mRNA), and the translation of such mRNA into polypeptide(s). If the final desired product is a biochemical, expression includes the creation of that biochemical and any precursors. Expression of a gene produces a "gene product." As used herein, a gene product can be either a nucleic acid, *e.g.*, a messenger RNA produced by transcription of a gene, or a polypeptide that is translated from a transcript. Gene products described herein further include nucleic acids with post transcriptional modifications, *e.g.*, polyadenylation, or polypeptides with post translational modifications, *e.g.*, methylation, glycosylation, the addition of lipids, association with other protein subunits, proteolytic cleavage, and the like.

[0084] The term “eukaryote” or “eukaryotic organism” is intended to encompass all organisms in the animal, plant, and protist kingdoms, including protozoa, fungi, yeasts, green algae, single celled plants, multi celled plants, and all animals, both vertebrates and invertebrates. The term does not encompass bacteria or viruses. A “eukaryotic cell” is

intended to encompass a singular “eukaryotic cell” as well as plural “eukaryotic cells,” and comprises cells derived from a eukaryote.

[0085] The term “vertebrate” is intended to encompass a singular “vertebrate” as well as plural “vertebrates,” and comprises mammals and birds, as well as fish, reptiles, and amphibians.

[0086] The term “mammal” is intended to encompass a singular “mammal” and plural “mammals,” and includes, but is not limited to humans; primates such as apes, monkeys, orangutans, and chimpanzees; canids such as dogs and wolves; felids such as cats, lions, and tigers; equids such as horses, donkeys, and zebras, food animals such as cows, pigs, and sheep; ungulates such as deer and giraffes; rodents such as mice, rats, hamsters and guinea pigs; and bears. In certain aspects, the mammal is a human subject.

[0087] The terms “tissue culture” or “cell culture” or “culture” or “culturing” refer to the maintenance or growth of plant or animal tissue or cells in vitro under conditions that allow preservation of cell architecture, preservation of cell function, further differentiation, or all three. “Primary tissue cells” are those taken directly from tissue, *i.e.*, a population of cells of the same kind performing the same function in an organism. Treating such tissue cells with the proteolytic enzyme trypsin, for example, dissociates them into individual primary tissue cells that grow or maintain cell architecture when seeded onto culture plates. Cell cultures arising from multiplication of primary cells in tissue culture are called “secondary cell cultures.” Most secondary cells divide a finite number of times and then die. A few secondary cells, however, can pass through this “crisis period,” after which they are able to multiply indefinitely to form a continuous “cell line.” The liquid medium in which cells are cultured is referred to herein as “culture medium” or “culture media.” Culture medium into which desired molecules, *e.g.*, viruses or proteins, *e.g.*, immunoglobulin molecules, have been secreted during culture of the cells therein can be referred to as “conditioned medium.”

[0088] As used herein, the term “identify” refers to methods in which a desired molecule, *e.g.*, a polynucleotide encoding a protein of interest with a desired characteristics or function, is differentiated from a plurality or library of such molecules. Identification methods include “selection” and “screening” or “panning.” As used herein, “selection” methods are those in which the desired molecules can be directly separated from the library, *e.g.*, via drug resistance. As used herein, “screening” or “panning” methods are those in which pools comprising the desired molecules are subjected to an assay in which the desired molecule

can be detected. Aliquots of the pools in which the molecule is detected are then divided into successively smaller pools which are likewise assayed, until a pool which is highly enriched from the desired molecule is achieved.

Poxviruses, *e.g.*, vaccinia virus EEV vectors

[0089] IMP fusion proteins as provided herein are produced in poxvirus vectors, *e.g.*, vaccinia virus vectors. The term “poxvirus” includes any member of the family Poxviridae. See, for example, B. Moss in: Virology, 2d Edition, B. N. Fields, D. M. Knipe *et al.*, Eds., Raven Press, p. 2080 (1990). The genus of orthopoxvirus includes, *e.g.*, vaccinia virus, variola virus (the virus that causes smallpox), and raccoon poxvirus. Vaccinia virus is the prototype orthopoxvirus, and has been developed and is well-characterized as a vector for the expression of heterologous proteins.

[0090] In those embodiments where poxvirus vectors, in particular vaccinia virus vectors, are used to express IMP fusion proteins as provided herein, any suitable poxvirus vector can be used. In certain aspects, the location of a gene encoding an IMP fusion protein can be in a region of the vector that is non-essential for growth and replication of the virus so that infectious viruses are produced. Although a variety of non-essential regions of the vaccinia virus genome have been characterized, the most widely used locus for insertion of foreign genes is the thymidine kinase locus, located in the HindIII J fragment in the genome. In certain vaccinia virus vectors, the tk locus has been engineered to contain one or two unique restriction enzyme sites, allowing for convenient use of the trimolecular recombination method recombinant virus production, as described elsewhere herein.

[0091] Polynucleotides encoding IMP fusion proteins as provided herein can be inserted into poxvirus vectors, particularly vaccinia virus vectors, under operable association with a transcriptional control region which functions in the cytoplasm of a poxvirus-infected cell.

[0092] Poxvirus transcriptional control regions comprise a promoter and a transcription termination signal. Gene expression in poxviruses is temporally regulated, and promoters for early, intermediate, and late genes possess varying structures. Certain poxvirus genes are expressed constitutively, and promoters for these “early-late” genes bear hybrid structures. Synthetic early-late promoters have also been developed. Suitable poxvirus promoters for expressing IMP fusion proteins as provided herein include, but are not limited to late promoters such as the 7.5-kD promoter, the MIL promoter, the 37-kD promoter, the 11-kD promoter, the 11L promoter, the 12L promoter, the 13L promoter, the 15L promoter, the 17L

promoter, the 28-kD promoter, the H1L promoter, the H3L promoter, the H5L promoter, the H6L promoter, the H8L promoter, the D11L promoter, the D12L promoter, the D13L promoter, the A1L promoter, the A2L promoter, the A3L promoter, and the P4b promoter. See, *e.g.*, Moss, B., "Poxviridae and their Replication" IN Virology, 2d Edition, B. N. Fields, D. M. Knipe *et al.*, Eds., Raven Press, p. 2090 (1990).

[0093] Suitable poxvirus vectors include wild-type vaccinia virus, *e.g.*, strain Western Reserve or WR, or attenuated vaccinia virus, *e.g.*, modified vaccinia Ankara (MVA) (Mayr, A. *et al.*, Infection 3:6-14 (1975)).

[0094] During its replication cycle, a poxvirus, *e.g.*, a vaccinia virus, produces four infectious forms which differ in their membrane structure: intracellular mature virion (IMV), the intracellular enveloped virion (IEV), the cell-associated enveloped virion (CEV) and the extracellular enveloped virion (EEV). The prevailing view is that the IMV have a single lipoprotein membrane, while the CEV and EEV are both surrounded by two membrane layers and the IEV has three envelopes. EEV is shed from the plasma membrane of the host cell and the EEV membrane is derived from the trans-Golgi.

[0095] After infection, the virus loses its membrane(s) and the DNA/protein core is transported along microtubules into the cell. The proteins encoded by early vaccinia mRNAs ("early" is defined as pre-DNA replication) lead to uncoating of the vaccinia core and subsequent DNA replication. This replication occurs in what are termed "viral factories" which are located essentially on top of the ER. Within the viral factory, immature virions (IV) assemble and are processed to form IMV (Intracellular Mature Virus). IMVs contain a membrane that is derived from the ER. The majority of IMVs are released from the cell by cell lysis. Some IMVs are transported on microtubules to sites of wrapping by membranes of the trans-Golgi network or early endosomes. The wrapping of the IMV particles by a double membrane creates a form of vaccinia called IEVs (Intracellular Enveloped Virus). The IEVs are then transported to the cell surface on microtubules. The outer IEV membrane fuses with the plasma membrane to expose a CEV (Cell Associated Enveloped Virus) at the cell surface. Actin polymerization from the host cell can drive the CEV to infect neighboring cells, or the virus can be released as an EEV. See, *e.g.*, Kim L. Roberts and Geoffrey L. Smith. Trends in Microbiology 16(10):472-479 (2008); Geoffrey L. Smith, *et al.*, Journal of General Virology 83:2915-2931 (2002).

- [0096] At least six virus-encoded proteins have been reported as components of the EEV envelope membrane. Of these, four proteins (A33R, A34R, A56R, and B5R) are glycoproteins, one (A36R) is a nonglycosylated transmembrane protein, and one (F13L) is a palmitoylated peripheral membrane protein. See, *e.g.*, Lorenzo *et al.*, *Journal of Virology* 74(22):10535 (2000). During infection, these proteins localize to the Golgi complex, where they are incorporated into infectious virus that is then transported and released into the extracellular medium. As provided herein, IMP fusion proteins are directed to and expressed on the EEV membrane as a fusion protein with an EEV-specific protein, *e.g.*, F13L or A56R.
- [0097] The F13L protein is associated with the interior surface of the outermost EEV membrane through palmitoylation of cysteines 185 and 186. Smith *Trends in Microbiol.* 16:472-479 (2008). Vaccinia viruses in which the gene encoding F13L is deleted form tiny plaques and the number of EEV produced is reduced significantly.
- [0098] The amino acid sequence of the F13L protein from vaccinia virus strain WR is presented as SEQ ID NO: 1. The two palmitoylated cysteine residues (amino acids 85 and 86 of SEQ ID NO: 1) are underlined. Since F13L does not cross the membrane, it does not have a transmembrane domain or signal peptide.

>F13L (SEQ ID NO: 1)

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MWPFASVPAGAKCRLVETLPENMDFRSDHLTTFECFNEIITL
AKKYIYIASFCCNPLSTTRGALIFDKLKEASEKGIKIIVLLDER
GKRNLGELQSHCPDINFITVNIDKKNNVGLLLGCFWVSDDE
RCYVGNASFTGGSIHITKTLGVYSDYPPLATDLRRRFDTFKA
FNSAKNSWLNLCSAACCLPVSTAYHIKNPIGGVFFTDSPEHL
LGYSRDLDTDVVIDKLKSAKTSIDIEHLAIVPTTRVDGNSYY
WPDYNSIIEAAINRGVKIRLLVGNWDKNDVYSMATARSLD
ALCVQNDLSVKVFTIQNNTKLLIVDDEYVHITSANFDGTHY
QNHGFVSFNSIDKQLVSEAKKIFERDWVSSHSKSLKI
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- [0099] The A56R protein is the vaccinia virus hemagglutinin, and is a standard type I integral membrane protein comprising an amino-terminal extracellular (“extra-membrane”) domain, a single transmembrane domain, and a cytoplasmic (“intra-membrane”) domain. A56R comprises an N-terminal signal peptide of about 33 amino acids, an Ig-like domain extending from about amino acid 34 to about amino acid 103, a stalk region extending from about amino acid 121 to about amino acid 275, a transmembrane domain extending from about amino acid 276 to about amino acid 303, and an cytoplasmic (“inter-membrane”) domain extending from about amino acid 304 to amino acid 314. See DeHaven *et al.*, *J. Gen Virol.* 92:1971-1980 (2011). A56R is presented as SEQ ID NO: 5.

>A56R (SEQ ID NO: 5)

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MTRLPILLLLISLVYATPFPQTSKKIGDDATLSCNRNNTNDY
VVMSAWYKEPNISIILLAAKSDVLYFDNYTKDKISYDSPYDD
LVTTITIKSLTARDAGTYVCAFFMTSTTNDTDKVDYEEYSTE
LIVNTDSESTIDIILSGSTHSPETSSKKPDYIDNSNCSSVFEIAT
PEPITDNVEDHTDTVTYTSDSINTVSASSGESTTDETPEPITD
KEDHTVTDTVSYTTVSTSSGIVTTKSTTDDADLYDTYNDND
TVPPTTVGGSTTSISNYKTKDFVEIFGITALIILSAVAIFCITYY
IYNKRSRKYKTENKV
```

[0100] IMP fusion proteins as provided herein can be expressed in any suitable vaccinia virus. In certain embodiments, the DNA encoding an EEV fusion protein can be inserted into a region of the vaccinia virus genome which is non-essential for growth and replication of the vector so that infectious viruses are produced. Although a variety of non-essential regions of the vaccinia virus genome have been characterized, the most widely used locus for insertion of foreign genes is the thymidine kinase locus, located in the HindIII J fragment in the genome. IMP fusion proteins as provided herein can be inserted into vaccinia virus vectors under operable association with a transcriptional control region which functions in the cytoplasm of a poxvirus-infected cell.

[0101] Suitable promoters for use in the methods described herein include, without limitation, the early/late 7.5-kD promoter, or the early/late H5 promoter (or variants thereof).

The Tri-Molecular Recombination Method

[0102] Tri-molecular recombination, as disclosed in Zauderer, PCT Publication No. WO 00/028016 and in US Patent No. 7,858,559, is a high efficiency, high titer-producing method for expressing proteins of interest and or producing libraries in vaccinia virus. The tri-molecular recombination method allows the generation of recombinant viruses at efficiencies of at least 90%, and titers at least at least 2 orders of magnitude higher than those obtained by direct ligation.

[0103] In certain aspects, IMP fusion proteins for expression in vaccinia virus and display on EEV as described herein can be constructed in poxvirus vectors, *e.g.*, vaccinia virus vectors, by tri-molecular recombination.

[0104] In certain embodiments, a transfer plasmid for IMP fusion proteins for expression in EEV is provided, which comprises a polynucleotide flanking regions in the vaccinia virus Tk gene, the vaccinia virus H5 promoter, and NcoI and BsiWI restriction sites for inserting coding regions for desired fusion proteins.

Integral membrane proteins

[0105] The disclosure provides a method for expressing integral membrane proteins (IMPs) in a conformationally intact state that approaches the native conformation of the protein as it would appear in a cell in which the protein is naturally expressed. According to the disclosure, IMPs are expressed as fusion proteins with poxvirus proteins that are expressed on poxvirus, *e.g.*, vaccinia virus EEVs. IMP fusion proteins as provided herein, when expressed and displayed on the surface of EEVs, are useful as target antigens for screening libraries of binding molecules, *e.g.*, antibody display libraries.

[0106] Any IMP can be constructed as a fusion protein according to the methods provided herein. In certain aspects the IMP is a target for immunotherapy. In certain aspects the IMP is a multi-pass IMP such as CD20 or a G-protein coupled receptor (GPCR). Suitable multi-pass human IMPs for use in the construction of IMP fusion proteins as provided herein include, without limitation, the proteins listed in Table 1.

Table 1: Exemplary Human Multi-Pass Integral Membrane Proteins

Protein Name	ENTREZ_gene_ID	ENTREZ gene symbol	# predicted TM domains
Poliovirus receptor-related protein 3	25945	PVRL3	2
Prominin-1	8842	PROM1	5
FL cytokine receptor	2322	FLT3	2
Scavenger receptor cysteine-rich type 1 protein M130	9332	CD163	2
C-X-C chemokine receptor type 1	3577	CXCR1	6
C-X-C chemokine receptor type 3	2833	CXCR3	7
C-X-C chemokine receptor type 5	643	CXCR5	7
C-C chemokine receptor type 4	1233	CCR4	7
C-C chemokine receptor type 7	1236	CCR7	7
B-lymphocyte antigen CD20	931	MS4A1	4
Major prion protein	5621	PRNP	2
Plexin-C1	10154	PLXNC1	2
Multidrug resistance protein 1	5243	ABCB1	12
Putative G-protein coupled receptor 44	11251	GPR44	7
EGF-like module-containing mucin-like hormone receptor-like 2	30817	EMR2	7
Frizzled-4	8322	FZD4	9
Leukocyte surface antigen CD47	961	CD47	5
CD63 antigen	967	CD63	4
Choline transporter-like protein 1	23446	SLC44A1	9

Protein Name	ENTREZ_gene_ID	ENTREZ gene symbol	# predicted TM domains
CD97 antigen	976	CD97	7
Multidrug resistance-associated protein 1	4363	ABCC1	16
CAS1 domain-containing protein 1	64921	CASD1	14
Solute carrier family 12 member 6	9990	SLC12A6	14
Sodium/hydrogen exchanger 1	6548	SLC9A1	13
Solute carrier family 12 member 9	56996	SLC12A9	13
Solute carrier family 2, facilitated glucose transporter member 1	6513	SLC2A1	12
Sodium- and chloride-dependent taurine transporter	6533	SLC6A6	12
Solute carrier organic anion transporter family member 4A1	28231	SLCO4A1	12
Solute carrier family 23 member 2	9962	SLC23A2	12
Solute carrier organic anion transporter family member 3A1	28232	SLCO3A1	12
Prestin	375611	SLC26A5	11
Equilibrative nucleoside transporter 2	3177	SLC29A2	11
Equilibrative nucleoside transporter 1	2030	SLC29A1	11
Sodium-coupled neutral amino acid transporter 1	81539	SLC38A1	11
Sodium bicarbonate cotransporter 3	9497	SLC4A7	11
Urea transporter 1	6563	SLC14A1	10
Transmembrane and coiled-coil domain-containing protein 3	55002	TMCO3	10
Signal peptide peptidase-like 2A	84888	SPPL2A	9
Transmembrane 9 superfamily member 3	56889	TM9SF3	9
Anoctamin-9	338440	ANO9	8
Sodium/potassium-transporting ATPase subunit alpha-1	476	ATP1A1	8
Sodium/potassium-transporting ATPase subunit alpha-3	478	ATP1A3	8
Anoctamin-6	196527	ANO6	8
V-type proton ATPase 116 kDa subunit a isoform 2	23545	ATP6V0A2	8
Putative P2Y purinoceptor 10	27334	P2RY10	7
G-protein coupled receptor 39	2863	GPR39	7
Sphingosine 1-phosphate receptor 2	9294	S1PR2	7
Latrophilin-2	23266	LPHN2	7
Beta-2 adrenergic receptor	154	ADRB2	7
Alpha-2C adrenergic receptor	152	ADRA2C	7
Thromboxane A2 receptor	6915	TBXA2R	7
Platelet-activating factor receptor	5724	PTAFR	7
Proteinase-activated receptor 1	2149	F2R	7
Neuropeptide Y receptor type 1	4886	NPY1R	7

Protein Name	ENTREZ_gene_ID	ENTREZ gene symbol	# predicted TM domains
Type-1 angiotensin II receptor	185	AGTR1	7
Neurotensin receptor type 1	4923	NTSR1	7
Cannabinoid receptor 2	1269	CNR2	7
Prostaglandin E2 receptor EP2 subtype	5732	PTGER2	7
Calcitonin gene-related peptide type 1 receptor	10203	CALCRL	7
Protein GPR107	57720	GPR107	7
G-protein coupled receptor 126	57211	GPR126	7
P2Y purinoceptor 8	286530	P2RY8	7
Probable G-protein coupled receptor 125	166647	GPR125	7
Transmembrane protein 87A	25963	TMEM87A	7
Mas-related G-protein coupled receptor member F	116535	MRGPRF	7
Transmembrane protein 87B	84910	TMEM87B	7
Proteinase-activated receptor 4	9002	F2RL3	7
Smoothed homolog	6608	SMO	7
EGF-like module-containing mucin-like hormone receptor-like 3	84658	EMR3	7
Neuromedin-U receptor 1	10316	NMUR1	7
EGF, latrophilin and seven transmembrane domain-containing protein 1	64123	ELTD1	7
Transmembrane protein 8A	58986	TMEM8A	7
Cadherin EGF LAG seven-pass G-type receptor 2	1952	CELSR2	7
Cadherin EGF LAG seven-pass G-type receptor 1	9620	CELSR1	7
Cadherin EGF LAG seven-pass G-type receptor 3	1951	CELSR3	7
Cysteinyl leukotriene receptor 1	10800	CYSLTR1	7
G-protein coupled receptor 56	9289	GPR56	7
Lipid phosphate phosphohydrolase 1	8611	PPAP2A	6
Potassium voltage-gated channel subfamily A member 3	3738	KCNA3	6
Zinc transporter ZIP6	25800	SLC39A6	6
Zinc transporter ZIP14	23516	SLC39A14	6
P2Y purinoceptor 11	5032	P2RY11	6
Zinc transporter ZIP10	57181	SLC39A10	6
Cytochrome b-245 heavy chain	1536	CYBB	5
Prominin-2	150696	PROM2	5
Protein tweety homolog 2	94015	TTYH2	5
Protein tweety homolog 3	80727	TTYH3	5
Gamma-aminobutyric acid receptor subunit beta-3	2562	GABRB3	4
Glutamate receptor, ionotropic kainate 3	2899	GRIK3	4
Neuronal membrane glycoprotein M6-b	2824	GPM6B	4
Metal transporter CNNM4	26504	CNNM4	4

Protein Name	ENTREZ_gene_ID	ENTREZ gene symbol	# predicted TM domains
Metal transporter CNNM3	26505	CNNM3	3
Discoidin, CUB and LCCL domain-containing protein 2	131566	DCBLD2	3
Transmembrane protein 131-like	23240	KIAA0922	2
Leucine-rich repeat transmembrane protein FLRT2	23768	FLRT2	2
Attractin	8455	ATRN	2
Receptor-type tyrosine-protein phosphatase gamma	5793	PTPRG	2
Interferon alpha/beta receptor 2	3455	IFNAR2	2
Ephrin type-A receptor 5	2044	EPHA5	2
Tyrosine-protein kinase transmembrane receptor ROR1	4919	ROR1	2
Tomoregulin-1	8577	TMEFF1	2
P2X purinoceptor 7	5027	P2RX7	2
TM2 domain-containing protein 3	80213	TM2D3	2
TM2 domain-containing protein 1	83941	TM2D1	2
G-protein coupled receptor 64	10149	GPR64	8
Psychosine receptor	8477	GPR65	6
Large neutral amino acids transporter small subunit 1	8140	SLC7A5	12
Sphingosine 1-phosphate receptor 3	1903	S1PR3	7
Solute carrier organic anion transporter family member 2A1	6578	SLCO2A1	12
Type-2 angiotensin II receptor	186	AGTR2	7
UPF0513 transmembrane protein	79583	UNQ870/PRO1886	2
Lipid phosphate phosphohydrolase 3	8613	PPAP2B	5
Blood vessel epicardial substance	11149	BVES	3
Sodium/potassium/calcium exchanger 6	80024	SLC24A6	13
5-hydroxytryptamine receptor 2B	3357	HTR2B	7
Mucolipin-1	57192	MCOLN1	6
Cadherin-8	1006	CDH8	2
Adenosine receptor A1	134	ADORA1	7
Probable G-protein coupled receptor 110	266977	GPR110	7
Chemokine receptor-like 1	1240	CMKLR1	7
Proton-coupled folate transporter	113235	SLC46A1	11
Sphingosine 1-phosphate receptor 4	8698	S1PR4	7
Protein FAM171A2	284069	FAM171A2	2
Alpha-2A adrenergic receptor	150	ADRA2A	7
C-X-C chemokine receptor type 7	57007	CXCR7	7
Apelin receptor	187	APLNR	7
Probable G-protein coupled receptor 116	221395	GPR116	7
Metalloreductase STEAP4	79689	STEAP4	6

Protein Name	ENTREZ_gene_ID	ENTREZ gene symbol	# predicted TM domains
Solute carrier organic anion transporter family member 4C1	353189	SLCO4C1	12
ATP-binding cassette sub-family A member 8	10351	ABCA8	14
Vasoactive intestinal polypeptide receptor 1	7433	VIPR1	7
SID1 transmembrane family member 2	51092	SIDT2	11
Equilibrative nucleoside transporter 4	222962	SLC29A4	10
Succinate receptor 1	56670	SUCNR1	7
Metal transporter CNNM2	54805	CNNM2	4
Probable palmitoyltransferase ZDHHC5	25921	ZDHHC5	4
Solute carrier family 22 member 16	85413	SLC22A16	12
Leukotriene B4 receptor 1	1241	LTB4R	7
Pannexin-1	24145	PANX1	4
Sodium-dependent glucose transporter 1	91749	NAGLT1	11
Sodium/calcium exchanger 1	6546	SLC8A1	10
Neuronal acetylcholine receptor subunit alpha-3	1136	CHRNA3	4
Retinoic acid-induced protein 3	9052	GPRC5A	7
Lysophosphatidic acid receptor 5	57121	LPAR5	7
Probable G-protein coupled receptor 132	29933	GPR132	7
Sphingosine 1-phosphate receptor 5	53637	S1PR5	7
Endothelin-1 receptor	1909	EDNRA	7
Probable G-protein coupled receptor 124	25960	GPR124	7
Solute carrier family 12 member 7	10723	SLC12A7	12
Thyrotropin receptor	7253	TSHR	7
Transient receptor potential cation channel subfamily V member 2	51393	TRPV2	6
Glutamate receptor delta-1 subunit	2894	GRID1	4
Gamma-aminobutyric acid receptor subunit alpha-2	2555	GABRA2	4
Sphingosine 1-phosphate receptor 1	1901	S1PR1	7
Prostaglandin E2 receptor EP3 subtype	5733	PTGER3	7
Probable G-protein coupled receptor 174	84636	GPR174	7
Glutamate receptor 2	2891	GRIA2	3
Amiloride-sensitive sodium channel subunit delta	6339	SCNN1D	2
5-hydroxytryptamine receptor 1D	3352	HTR1D	7
Goliath homolog	55819	RNF130	2
ATP-binding cassette sub-family A member 7	10347	ABCA7	11
Prostacyclin receptor	5739	PTGIR	7
Probable G-protein coupled receptor 176	11245	GPR176	7
Thyrotropin-releasing hormone receptor	7201	TRHR	7
Claudin-12	9069	CLDN12	4
Protein FAM38A	9780	FAM38A	29

Protein Name	ENTREZ_gene_ID	ENTREZ gene symbol	# predicted TM domains
Niemann-Pick C1 protein	4864	NPC1	13
Synaptic vesicle glycoprotein 2A	9900	SV2A	12
Signal peptide peptidase-like 2B	56928	SPPL2B	9
Rhomboid family member 2	79651	RHBDF2	7
Immunoglobulin superfamily member 1	3547	IGSF1	4
Dolichyl-diphosphooligosaccharide--protein glycosyltransferase subunit 2	6185	RPN2	3
Transmembrane emp24 domain-containing protein 9	54732	TMED9	2
Steryl-sulfatase	412	STS	2
Transmembrane 9 superfamily member 1	10548	TM9SF1	9
Melanoma inhibitory activity protein 3	375056	MIA3	2
Arylsulfatase F	416	ARSF	2
Solute carrier family 2, facilitated glucose transporter member 4	6517	SLC2A4	12
Anoctamin-5	203859	ANO5	8
Nicalin	56926	NCLN	2

[0107] In certain aspects, the multi-pass IMP is a GPCR, *e.g.*, FZD4 or CXCR4. In certain aspects the multi-pass IMP is CD20.

Polynucleotides encoding IMP fusion proteins for expression on poxvirus EEV

[0108] This disclosure provides an isolated polynucleotide for expression of an integral membrane protein or fragment thereof in a conformationally-intact form in the context of a biological membrane, as a fusion with a protein or fragment thereof specific for vaccinia virus EEV. By “conformationally intact” is meant that the protein appears, or is displayed, in a native or close to native conformation in the context of a biological lipid bilayer membrane, much as the protein would appear in its native state.

[0109] In one aspect, the disclosure provides an isolated polynucleotide that includes a first nucleic acid fragment that encodes an integral membrane protein (IMP) or fragment thereof, *e.g.*, a multi-pass IMP, where the IMP or fragment thereof comprises at least one extra-membrane region, at least one transmembrane domain and at least one intra-membrane region, and where a portion of the first nucleic acid fragment encoding at least one intra-membrane region is situated at the 5' or 3' end of the first nucleic acid fragment; and a second nucleic acid fragment that encodes a vaccinia virus F13L protein (SEQ ID NO: 1) or functional fragment thereof, where the second nucleic acid fragment is fused in frame to a portion of the first nucleic acid fragment that encodes an intra-membrane region of the IMP.

The first nucleic acid fragment and the second nucleic acid fragment can, in some instances, be separated by a nucleic acid encoding a linker or other spacer. The polynucleotide can further include a poxvirus promoter operably associated with the first and second nucleic acid fragments, allowing expression of the polynucleotide in the cytoplasm of a poxvirus-infected cell. According to this aspect, a poxvirus-infected cell that contains the polynucleotide can express an IMP-F13L fusion protein as part of the outer envelope membrane of an extracellular enveloped virion (EEV). Schematic diagrams showing expression of an IMP as a fusion with F13L are shown in **FIG. 1B** and **FIG. 1C**.

[0110] In certain aspects, the IMP or fragment thereof can be a multi-pass membrane protein comprising at least two, at least three, at least four, at least five, at least six, at least seven, at least eight, at least nine, at least ten, at least eleven, at least twelve, or even more transmembrane (TM) domains, such as those listed in Table 1.

[0111] Where the IMP has an odd number of TM domains, one end of the IMP, either the N-terminus or the C-terminus, will be naturally situated on the extra-membrane side of the biological membrane and the other end of the IMP will be situated on the intra-membrane side of the IMP. Since the F13L protein is wholly-internal to the outer membrane of poxvirus EEVs, the end of the IMP, the N-terminus or the C-terminus that is situated internal to the membrane can be fused to F13L. Thus for an IMP such as a typical 7-TM domain GPCR in which the N-terminus of the protein is extra-membrane and the C-terminus is intra-membrane, the N-terminus of F13L can be fused to the C-terminus of the GPCR as shown in **FIG. 1B**. Accordingly, a polynucleotide as above is provided where the first nucleic acid fragment encodes an IMP with an odd number of transmembrane domains, where the 5' end of the first nucleic acid fragment encodes the extra-membrane region, and the 3' end of the first nucleic acid fragment encodes the intra-membrane region of the IMP, the latter being fused to the 5' end of the nucleic acid fragment encoding F13L or a fragment thereof.

[0112] In an exemplary polynucleotide of this type, the first polynucleotide can encode the human frizzled-4 protein (FZD4), or a fragment thereof, a target for immunotherapy of certain human cancers, fused to the N-terminus of F13L. Accordingly, a polynucleotide which encodes an FZD4-F13L fusion protein is provided. An exemplary polynucleotide according to this aspect encodes the mature fusion protein, amino acids 20 to 892 of SEQ ID NO: 2, as shown below. The polynucleotide can further encode a signal peptide, *e.g.*, the signal peptide of FZD4, amino acids 1 to 19 of SEQ ID NO: 2.

FZD(FL)-F13L (SEQ ID NO: 2)

MGWSCIIILFLVATATGAHS**FGDEEERRCDPIRISMCQNLGYNVTK**
MPNLVGHELQTD AELQLTFTPLIQYGCSSQLQFFLCSVYVPMCT
EKINIPIGPCGGMCLSVKRRCEPVLKEFGFAWPESLNC SKFPQN
DHNHMCMEGPGDEEVPLPHKTPIQPGEECHSVGTNSDQYIWVKRS
LNCVLKCGYDAGLYSRSAKEFTDIWMAVWASLCFISTAFTVLTFL
IDSSRFSYPERPIIFLSMCYNIYSIAYIVRLTVGRERISCD FEEA
AEPVLIQEGLKNTGCAIIFLLMYFFGMASSIWWVILTTLTWFLAAG
LKWGHEAIEMHSSYFHIAAWAIPAVKTIVILIMRLVDADEL TGLC
YVGNQNLDA LTGFVVAPLFTYL VIGTLFIAAGLVALFKIRSNLQK
DGKTDKLERLMVKIGVFSVLYTVPATCVIACYFYEISNWALFRY
SADDSNMAVEMLKIFMSLLVGITSGMWIWSAKTLHTWQKCSNRLV
NSGKVKREKRGNGWVKPGKGSE TVVMWPFASVPAGAKCRLVETLP
ENMDFRSDHLTTFE CFNEIITLAKKYIYIAS FCCNPLSTTRGALI
FDKLKEASEKGIKIIVLLDERGKRN LGELQSHCPDINFITVNIDK
KNNVGLLLGCFWVSDDERCYVGNASFTGGS IHTIKTLGVYSDYPP
LATDLRRRFDTFKAFNSAKNSWNLCSAACCLPVSTAYHIKNPIG
GVFFTDSP EHL LGYSRDLDTDVVIDKLKSAKTSIDIEHLAIVPTT
RVDGNSYYWPD IYNSIIEAAINRGVKIRLLVGNWDKNDVYSMATA
RSLDALCVQNDLSVKVFTIQNNTKLLIVDDEYVHITSANFDGTHY
QNHGFVSFNSIDKQLVSEAKKIFERDWVSSHSLKI

Single Underline - leader peptide (amino acids 1-19)

Bold - human Fzd4 (amino acids 20-520)

Italics - F13L (amino acids 521-892)

[0113] In another exemplary polynucleotide of this type, the first polynucleotide can encode A CXC chemokine receptor, or a fragment thereof, fused to the N-terminus of F13L. CXC chemokine receptors are likewise targets for immunotherapy of certain human cancers. An exemplary CXC chemokine receptor is CXCR4, or a fragment thereof. Accordingly, a polynucleotide which encodes a CXC chemokine receptor-F13L fusion protein, *e.g.*, a CXCR4-F13L fusion protein is provided. An exemplary polynucleotide according to this aspect encodes SEQ ID NO: 3, as shown below.

CXCR4-F13L (SEQ ID NO: 3)

MAIPLPLLQIYTS DNYTEEMGSGDYDSMKEPCFREANANFNKIFL
PTIYSIIFLTGIVGNGLVILVMGYQKKLRSM TDKYRLHLSVADLL
FVITLPFWAVDAVANWYFGNFLCKAVHVIYTVNLYSSVLILAFIS
LDRYLAIVHATNSQRPRKLLAEKVYVGVWIPALLLTIPDFIFAN
VSEADDRYICDRFYPN DLWVVVFQFQHIMVGLILPGIVILSCYCI
IISKLSHSGHQKRKALKTTVILILAFFACWLPYYIGISIDSFIL
LEIIKQGC EFENTVHKWISITEALAFFHCCLNPILYAFLGAKFKT
SAQHALTSVSRGSSLKILSKGKRGGHSSVSTESESSSFHSS*MWPF*
ASVPAGAKCRLVETLPENMDFRSDHLTTFE CFNEIITLAKKYIYI
ASFCCNPLSTTRGALIFDKLKEASEKGIKIIVLLDERGKRN LGEL
QSHCPDINFITVNIDK KNNVGLLLGCFWVSDDERCYVGNASFTGG
SIHTIKTLGVYSDYPP LATDLRRRFDTFKAFNSAKNSWNLCSAA
CCLPVSTAYHIKNPIGGVFFTDSP EHL LGYSRDLDTDVVIDKLKS

*AKTSIDIEHLAIVPTTRVDGNSYYWPDIIYNSIIEAAINRGVKIRL
LVGNWDKNDVYSMATARSLDALCVQNDLSVKVFTIQNNTKLLIVD
DEYVHITSANFDGTHYQNHGFVSFNSIDKQLVSEAKKIFERDWVS
SHSKSLKI*

Bold – human CXCR4 (amino acids 1-356)

Italics – F13L (amino acids 357-728)

[0114] As will be evident to a person of ordinary skill in the art, a multi-pass membrane protein having an even number of transmembrane domains will be inserted into a biological membrane such that its N-terminus and its C-terminus are on the same side of the membrane, either on the extra-membrane side of the membrane, or on the intra-membrane side of the membrane. Since the F13L protein is situated entirely on the intra-membrane side of poxvirus EEVs, formation of an IMP-F13L fusion protein properly embedded in the membrane would need at least one of the N-terminus or the C-terminus of the IMP or fragment thereof to be internal to the membrane. Where the IMP has an even number of TM domains and both are situated internally, the F13L protein can be fused either to the N-terminus of the IMP or to the C-terminus of the IMP. If the full-length IMP is situated such that both the N- and C-terminus are extra-membrane, a fragment of the IMP having an odd number of TM domains can be fused to F13L.

[0115] Accordingly, the disclosure provides a polynucleotide as described above that encodes an IMP with an even number of transmembrane domains, where both the 5' and 3' ends of the first nucleic acid fragment encode intra-membrane regions. In certain aspects the 3' end of the nucleic acid fragment encoding F13L can be fused to the 5' end of the nucleic acid fragment encoding the IMP, in certain aspects the 5' end of the nucleic acid fragment encoding F13L can be fused to the 3' end of the nucleic acid fragment encoding the IMP.

[0116] An exemplary IMP of this type is human CD20, a 4-TM domain IMP expressed on human B cells, which is a target for immunotherapy of B cell leukemias, lymphomas, and myelomas. A diagram of a CD20-F13L fusion protein in which the C-terminus of CD20 is fused to the N-terminus of F13L is shown in **FIG. 1C**. Accordingly, a polynucleotide which encodes a CD20-F13L fusion protein is provided. An exemplary polynucleotide according to this aspect encodes SEQ ID NO: 4, as shown below.

CD20-F13L (Seq ID NO: 4)

**MATPRNSVNGTFPAEPMKGPIAMQSGPKPLFRRMSSLVGPTQSFF
MRESKTLGAVQIMNGLFHIALGGLLMIPAGIYAPICVTVWYPLWG
GIMYIISGSLLAATEKNSRKCLVKGMIMNSLSLFAAISGMILSI
MDILNIKISHFLKMESLNFIRAHTPYINIYNCEPANPSEKNSPST**

QYCYSIQSLFLGILSVMLIFAFFQELVIAGIVENEWKRTCSRPKS
NIVLLSAEEKKEQTIEIKEEVVGLTETSSQPKNEEDIEIPIQEE
EEEEETETNFPEPPQDQESSPIENDSSPMWPFASVPAGAKCRLVET
LPENMDFRSDHLTTFECFNEIITLAKKYIYIASFCCNPLSTTRGA
LIFDKLKEASEKGIKIIVLLDERGKRNLGELQSHCPDINFITVNI
DKKNNVGLLLGCFWVSDDERCYVGNASFTGGSIHITIKTLGVYSDY
PPLATDLRRRFDTFKAFNSAKNSWLNLCSAACCLPVSTAYHIKNP
IGGVFFTDSPHLLGYSRDLDTDVIDKLKSAKTSIDIEHLAIVP
TTRVDGNSYYWPDYNSIIEAAINRGVKIRLLVGNWDKNDVYSMA
TARSLDALCVQNDLSVKVFTIQNNTKLLIVDDEYVHITSANFDGT
HYQNHGFVSFNSIDKQLVSEAKKIFERDWWSSHSLKI

Bold – human CD20 (MS4A1) (amino acids 1-298)

Italics – F13L (amino acids 299-669)

- [0117] In polynucleotides as provided above, the first and second nucleic acid fragments can be directly fused, or alternatively they can be separated by a nucleic acid fragment encoding a linker or spacer or other polypeptide fragment. In certain aspects, a polynucleotide as provided above can further include a third nucleic acid fragment that encodes a heterologous peptide polypeptide, either between the first and second nucleic acid fragments, or on either side. The heterologous peptide can be, for example, a linker sequence, an amino acid tag or label, or a peptide or polypeptide sequence that facilitates purification. In certain aspects the heterologous peptide is a 6-histidine tag fused, *e.g.*, to the C-terminus of the fusion protein.
- [0118] In certain aspects, a polynucleotide as provided herein is operably associated with a poxvirus promoter. Suitable promoters are described elsewhere herein. In certain aspects the promoter is a poxvirus p7.5 promoter or a poxvirus H5 promoter.
- [0119] A polynucleotide as provided herein can be or can be part of, a poxvirus genome, where the poxvirus genome, upon introduction into a suitable permissive host cell, can produce infectious EEV that display the IMP-F13L fusion protein on their surface. In certain aspects the poxvirus genome is a vaccinia virus genome, *e.g.*, a vaccinia virus WR genome or an MVA genome. A poxvirus genome comprising a polynucleotide as described can be produced by standard molecular biological and virology techniques, for example by using tri-molecular recombination as described herein. A poxvirus genome as provided herein can be introduced into permissive cells as part of a recombinant poxvirus, or as naked DNA accompanied by suitable helper viruses, *e.g.*, fowlpox virus. The disclosure further provides a recombinant poxvirus, *e.g.*, a recombinant vaccinia virus comprising the provided poxvirus genome.

IMP-EEV fusion proteins, recombinant poxvirus EEVs, and methods of making

[0120] This disclosure further provides an IMP-F13L fusion protein such as those encoded by the polynucleotides described above. Moreover, the IMP-F13L fusion protein can be expressed on the surface of a recombinant poxvirus EEV, *e.g.*, a recombinant vaccinia virus EEV. A recombinant poxvirus EEV, *e.g.*, a recombinant vaccinia virus EEV comprising the provided fusion protein is provided by the disclosure. A recombinant poxvirus EEV can be produced by a method that includes infecting a host cell permissive for vaccinia virus infectivity with a vaccinia virus comprising a poxvirus genome as provided above, and recovering EEV released from the infected host cell. Accordingly, an IMP-F13L fusion protein encoded by a polynucleotide as described above, is provided.

[0121] Moreover the disclosure provides fusion proteins comprising an IMP or fragment thereof, which can be a multi-pass IMP, and single pass IMP, or even just the extracellular domain (ECD) of the IMP, fused to a poxvirus protein, *e.g.*, a vaccinia virus protein, specific for EEV, such as F13L, A56R, B5R, 33R, A34R, or A36R, an “IMP-EEV fusion protein.” Exemplary ECD fusion proteins are described below. An IMP-EEV fusion protein as provided herein can display the IMP, *e.g.*, a multi-pass IMP, single-pass IMP or ECD of an IMP, in a conformationally intact form on the surface of poxvirus EEV. For use in screening antibody display libraries for antigen binding domains that specifically bind to a target IMP, display of IMPs on the surface of poxvirus EEV offers many advantages over displaying IMPs on the surface of recombinant cells, *e.g.*, CHO cells, as is typical. For example the IMP can be expressed at higher density on EEV than on cells. Moreover, EEV express only about six different poxvirus proteins on their surface (*e.g.*, F13L, A56R, B5R, 33R, A34R, and A36R) as opposed to hundreds that might be expressed on the surface of cells. Finally, inactivated EEV expressing IMP-F13L fusion proteins as provided herein can be attached to solid supports, offering convenience in library screening.

[0122] Accordingly, this disclosure provides a method to display an integral membrane protein (IMP) or fragment thereof in a native conformation for use, *e.g.*, in screening antibody display libraries for antigen binding domains specific for the IMP. The method includes: infecting host cells permissive for poxvirus infectivity with a recombinant poxvirus that expresses the IMP or fragment thereof as a fusion protein with poxvirus EEV-specific protein or membrane-associated fragment thereof, where EEV produced by the infected host cell comprise the IMP as part of the EEV outer envelope membrane; and recovering EEV

released from the host cell. IMP. In certain aspects, the EEV-specific protein or fragment thereof can be the vaccinia virus A33R protein, A34R protein, A56R protein, B5R protein, A36R protein, F13L protein, any membrane-associated fragment thereof, or any combination thereof.

[0123] In certain aspects, the EEV-specific protein is F13L (SEQ ID NO: 1) or a functional fragment thereof, and the fusion protein can be one expressed by a polynucleotide as provided above, *e.g.*, where the IMP is a multi-pass membrane protein comprising at least two, at least three, at least four, at least five, at least six or at least seven transmembrane domains.

[0124] In certain aspects, the membrane-associated EEV specific protein fragment includes the stalk, transmembrane, and intra-membrane domains of the vaccinia virus A56R protein, a fragment comprising, consisting of, or consisting essentially of amino acids 108 to 314 of SEQ ID NO: 5. One of several exemplary fusion partners includes the ECD of human FZD4, shown in bold in SEQ ID NO: 6 below. According to this exemplary aspect the disclosure provides a method to display a conformationally intact fragment of human FZD4 on the surface of a poxvirus EEV comprising infecting host cells permissive for poxvirus infectivity with a recombinant poxvirus encoding a fusion protein comprising amino acids 20 to 370 of SEQ ID NO: 6. In certain aspects the fusion protein can further comprise a signal peptide, *e.g.*, amino acids 1 to 19 of SEQ ID NO: 6.

FZD-ECD-A56R (Seq ID NO: 6)
 MGWSCIIILFLVATATGAHS**FGDEEERRCDPIRISMCQNLGYNVTK**
MPNLVGHELQTDALQLTFTPLIQYGCSSQLQFFLCVYVPMCT
EKINIPIGPCGGMCLSVKRRCEPVLKEFGFAWPESLNCSEKFPQ
DHNHMCMEGPGDEEVPLPHKTPIQPGEE *TSTTNDTDKVDYEEYST*
ELIVNTDSESTIDIILSGSTHSPETSSKKPDYIDNSNCSSVFEIA
TPEPITDNVEDHTDTVTYTSDSINTVSASSGESTTDETPEPITDK
EDHTVTDTVSYTTVSTSSGIVTTKSTDDADLYDTYNDNDTVPPT
TVGGSTTISNYKTKDFVEIFGITALIILSAVAIFCITYYIYNKR
SRKYKTENKV.

Single Underline - leader peptide (amino acids 1-19)

Bold - human FZD4 extracellular domain (amino acids 20-163)

Italics - A56R stalk, transmembrane, and intra-membrane (amino acids 164 to 370)

[0125] Another exemplary fusion partner includes the ECD of human ErbB2 (Her2), shown in bold in SEQ ID NO: 7 below. According to this exemplary aspect the disclosure provides

a method to display a conformationally intact fragment of human Her2 on the surface of a poxvirus EEV comprising infecting host cells permissive for poxvirus infectivity with a recombinant poxvirus encoding a fusion protein comprising amino acids 20 to 855 of SEQ ID NO: 7. In certain aspects the fusion protein can further comprise a signal peptide, *e.g.*, amino acids 1 to 19 of SEQ ID NO: 7.

Her2-A56R (SEQ ID NO: 7)
MGWSCIIILFLVATATGAHS**STQVCTGTDMKLR**LPASPE THLDMLR
 HLY**QGCQVQGNLE**LT**YLP**TNASLS**FLQDIQEVQGYV**LIAHNQVR
 QVPL**QRLRIVRG**T**QLFEDNYALAVLDNGDPLNNT**TPVTGAS**PGGL**
 REL**QLRSLTEILKGGVLIQRNPQLCYQDTILWKDIFHKNNQ**LALT
 LIDTNRSRACHPCSPMCKGSR**CWGESSEDCQSLTR**TVCAGGCARC
 KGPLPTDC**HEQCAAGCTGPKHSDCLAC**LHFNHSGICELHCPALV
 TYNTDTFESMPNPEG**RYTFGASCVTAC**PYNYLSTDVG**SCTLVCPL**
 HNQE**VTAEDGTQ**RCEKCSKPCARVCYGLGMEHLREVR**AVTSANIQ**
 EFAGCKKIFGSLAFLPE**SFDGDPASNTAPLQPEQLQVFETLEEIT**
 GYLYISAWPDSL**PDLSVFQNLQVIRGRILHNGAYSLTLQGLGISW**
 LGLRSLRELGSGLALIH**HNTHLCFVHTVPWDQLFRNPHQALLHTA**
 NRPEDECVGEGLACH**QLCARGHCWGP**GPTQCVNCS**QFLRGQECVE**
 ECRVL**QGLPREYVNARHCLPCHPECQ**PQNGSVTCFGPEAD**QCVAC**
 AHYKDP**PF**CVARCP**SGVKPDL**SYMPIWKF**PDEEGACQPCPINCTH**
SCVDLDDKGCPAE**QRASP***TSTTNDTDKVDYEEYSTE*LIVNTDSES
TIDIILSGSTHSPETSSKKPDYIDNSNCSSVFEIATPEPITDNVE
DHTDTVTYTSDSINTVSASSGESTTDETPETIDKEDHTVTDTVS
YTTVSTSSGIVTTKSTTDDADLYDTYNDNDTVPPTTVGGSTTSIS
NYTKDFVEIFGITALIILSAVAIFCITYYYIYNKRSRKYKTENKV

•
 Single Underline - leader peptide (amino acids 1-19)
 Bold - human ERBB2 (HER2) extracellular domain (amino acids 20-648)
 Italics - A56R stalk, transmembrane, and intra-membrane (amino acids 649 to 855)

[0126] Another exemplary fusion partner includes the ECD of human CD100 (Semaphorin 4D), shown in bold in SEQ ID NO: 8 below. According to this exemplary aspect the disclosure provides a method to display a conformationally intact fragment of human CD100 on the surface of a poxvirus EEV comprising infecting host cells permissive for poxvirus infectivity with a recombinant poxvirus encoding a fusion protein comprising amino acids 20 to 935 of SEQ ID NO: 8. In certain aspects the fusion protein can further comprise a signal peptide, *e.g.*, amino acids 1 to 19 of SEQ ID NO: 8.

CD100-A56R (SEQ ID NO: 8)
MGWSCILFLVATATGAHS**FAPIPRITWEHREVHLVQFHE**
PDIYNYSALLLSEDKDTLYIGAREAVFAVNALNISEKQHE
VYWKVSEDKKAKCAEKGKSKQTECLNYIRVLQPLSATS
LYVCGTNAFQPACDHLNLTSEKFLGKNEDGKGRCFPDP
AHSYTSVMVDGELYSGTSYNFLGSEPIISRNSSHSPLRTEY
AIPWLNESFVFADVIRKSPDSPDGEDDRVYFFTEVSVE
YEFVFRVLIPRIARVCKGDQGGRLTLQKKWTSFLKARLI
CSRPDSSGLVFNVLRDVFLRSPGLKVPVFYALFTPQLNN
VGLSAVCAYNLSTAEVFSHGKYMQSTTVEQSHTKWVR
YNGPVPKPRPGACIDSEARAANYTSSLNLPDKTLQFVKD
HPLMDDSVTPIDNRPRLIKDVDNYTQIVVDRTQALDGTV
YDVMFVSTDRGALHKAISLEHAVHHEETQLFQDFEPVQ
TLLSSKKGNRFVYAGSNSGVVQAPLAFCGKHGTCEDC
VLARDPYCAWSPPTATCVALHQTESPSRGLIQEMSGDAS
VCPDKSKGSYRQHFFKHGGTAELKCSQKSNLARVFWKF
QNGVLKAESPKYGLMGRKNLLIFNLSEGD SGVYQCLSE
ERVKNKTVFQVVAKHVLEVKVVPKPVVAPTLSVVQTEG
SRIATKVLVASTQGSSPPTPAVQATSSGAILP PKPAPTGT
SCEPKIVINTVPQLHSEKTMYLKSSD*TSTTNDTDKVDYEEYS*
TELIVNTDSESTIDIILSGSTHSPETSSKKPDYIDNSNCSSVFEIATP
EPITDNVEDHTDVTYTSDSINTVSASSGESTTDETPETDKED
HTVTDTVSYTTVSTSSGIVTTKSTDDADLYDTYNDNDTVPTTV
GGSTTSISNYKTKDFVEIFGITALIILSAVAIFCITYYIYNKRSRYK
TENKV.

Single Underline – leader peptide (amino acids 1-19)

Bold – human CD100 extracellular domain (amino acids 20-728)

Italics – A56R stalk, transmembrane, and intra-membrane (amino acids 729 to 935)

- [0127] In certain aspects, the membrane-associated EEV specific protein fragment includes the transmembrane and intra-membrane domains of the vaccinia virus B5R protein, a fragment comprising, consisting of, or consisting essentially of amino acids 276 to 317 of SEQ ID NO: 9. In certain aspects, the membrane-associated EEV specific protein fragment includes the stalk, transmembrane, and intra-membrane domains of the vaccinia virus B5R protein, a fragment comprising, consisting of, or consisting essentially of amino acids 238 to 317 of SEQ ID NO: 9.

SEQ ID NO: 9: WR B5R protein

MKTISVVTLCLVLPVVYSTCTVPTMNNAKLTSTETSFNDK
QKVTFTCDQGYHSSDPNAV CETDKWKYENPCKKMCTVSD
YISELYNKPLYEVNSTMTLSCNGETKYFRCEEKNGNTSWND
TVTCPNAECQPLQLEHGSCQPVKEKYSFGEYMTINCVDGYE
VIGASYISCTANSWNVIPSCQQKCDMPSLSNGLISGSTFSIGG
VIHLSCKSGFTLTGSPSSTCIDGKWNPVLPICVRTNEEFDVPD

DGPDDETDLSKLSKDVVQYEQEIESLEATYHIIIVALTIMGVI
 FLISVIVLVCSCDKNNDQYKFHKLLP

[0128] In certain exemplary aspects the IMP fusion partner for the B5R fragment comprises the extracellular domain of human FZD4, shown in bold in SEQ ID NO: 10 and SEQ ID NO: 11 below. According to this exemplary aspect the disclosure provides a method to display a conformationally intact fragment of human FZD4 on the surface of a poxvirus EEV comprising infecting host cells permissive for poxvirus infectivity with a recombinant poxvirus encoding a fusion protein comprising amino acids 20 to 243 of SEQ ID NO: 10 or amino acids 20 to 281 of SEQ ID NO: 11. In certain aspects the fusion protein can further comprise a signal peptide, *e.g.*, amino acids 1 to 19 of SEQ ID NO: 10.

FZD-B5R (short) (SEQ ID NO: 10)

MGWSCILFLVATATGAYAFGDEEERRCDPIRISMCQNLG
YNVTKMPNLVGHELQTDALQLTTFTPLIQYGCSSQLQF
FLCSVYVPMCTEKINIPGCGGMCLSVKRRCEPVLKEF
GFAWPESLNCSEKFPQNDHNHMCMEGPGDEEVPLPHKT
PIQPGEECHSVGTNSDQYIWVKRSLNCVLKCGYDAGLYS
RSAKE*CATYHIIIVALTIMGVIFLISVIVLVCSCDKNNDQYKFHK*
LLP.

Single Underline – leader peptide (amino acids 1-19)

Bold – human FZD4 extracellular domain (amino acids 20-200)

Italics – B5R TM and cytoplasmic tail (amino acids 201-243)

FZD-B5R (long) (SEQ ID NO: 11)

MGWSCILFLVATATGAYAFGDEEERRCDPIRISMCQNLG
YNVTKMPNLVGHELQTDALQLTTFTPLIQYGCSSQLQF
FLCSVYVPMCTEKINIPGCGGMCLSVKRRCEPVLKEF
GFAWPESLNCSEKFPQNDHNHMCMEGPGDEEVPLPHKT
PIQPGEECHSVGTNSDQYIWVKRSLNCVLKCGYDAGLYS
RSAKEYVRTNEEFDPVDDGPDDETDLSKLSKDVVQYEQEIESL
EATYHIIIVALTIMGVIFLISVIVLVCSCDKNNDQYKFHKLLP.

Single Underline – leader peptide (amino acids 1-19)

Bold – human FZD4 extracellular domain (amino acids 20-200)

Italics – B5R stalk, TM and cytoplasmic tail (amino acids 201-281)

[0129] The disclosure further provides a fusion protein comprising: amino acids 20 to 892 of SEQ ID NO: 2; SEQ ID NO: 3; SEQ ID NO: 4; amino acids 20 to 370 of SEQ ID NO: 6; amino acids 20 to 855 of SEQ ID NO: 7; amino acids 20 to 935 of SEQ ID NO: 8; amino acids 20 to 243 of SEQ ID NO: 10; or amino acids 20 to 281 of SEQ ID NO: 11, any combination thereof, any fragment thereof, or any variant thereof, where the fusion protein,

when expressed by a recombinant poxvirus, appears on the surface of a poxvirus extracellular enveloped virion (EEV) in a native conformation.

[0130] A recombinant poxvirus EEV comprising any EEV fusion protein as provided herein is also provided.

Method of selecting antibodies

[0131] This disclosure further provides a method to select binding molecules, *e.g.*, antibodies, antigen-binding antibody fragments, or antibody like binding molecules that bind to a multi-pass membrane protein interest. The method comprises attaching a recombinant EEV as provided herein to a solid support, where the recombinant EEV can display a multi-pass protein on its surface; providing a display library, *e.g.*, an antibody display library, where the library comprises display packages displaying a plurality of antigen binding domains; contacting the display library with the EEV such that display packages displaying antigen binding domains that specifically binds to the IMP expressed on the EEV can bind thereto; removing unbound display packages; and recovering display packages that display an antigen binding domain specific for the IMP expressed on the EEV.

[0132] Any display library comprising a plurality of binding domains, *e.g.*, antibodies, antibody like molecules or other binding molecules is suitable for this method. For example the display library can be a phage display library, a yeast display library or a library constructed in a vaccinia virus vector as described elsewhere herein.

[0133] In certain aspects, the recombinant EEV can be inactivated prior to attachment to the solid support. For example, the EEV can be inactivated by incubation with Psoralen (Trioxsalen, 4'-aminomethyl-, hydrochloride) in the presence of UV irradiation.

[0134] Any suitable solid support can be used. As used herein, a "solid support" is any support capable of binding an EEV, which can be in any of various forms, as is known in the art. Well-known supports include tissue culture plastic, glass, polystyrene, polypropylene, polyethylene, dextran, nylon, amylases, natural and modified celluloses, polyacrylamides, gabbros, and magnetite. The nature of the carrier can be either soluble to some extent or insoluble for the purposes of this disclosure. The support material can have virtually any structural configuration as long as the coupled EEV is capable of binding to a displayed binding molecule such as an antibody. Thus, the support configuration can be spherical, as in a bead, or cylindrical, as in the inside surface of a test tube, or the external surface of a rod. Alternatively, the surface can be flat such as a sheet, test strip, etc. Typical supports include

beads, *e.g.*, magnetic polystyrene beads such as DYNABEADS® that can be pulled out of suspension by a magnet. The support configuration can include a tube, bead, microbead, well, plate, tissue culture plate, petri plate, microplate, microtiter plate, flask, stick, strip, vial, paddle, etc., etc. A solid support can be magnetic or non-magnetic. Those skilled in the art will know many other suitable carriers for binding EEV as provided herein, or will be able to readily ascertain the same. In certain aspects, EEV as provided herein can be attached to the solid support via reaction with, *e.g.*, tosyl groups, epoxy groups, carboxylic acid groups, or amino groups attached to the surface. For example, EEV can be attached to the surface of tosyl-activated magnetic beads, *e.g.*, MYONE™ tosylactivated beads. Alternatively, the EEV can be biotinylated and attached to a streptavidin solid surface, *e.g.*, streptavidin coated magnetic beads.

[0135] This disclosure employs, unless otherwise indicated, conventional techniques of cell biology, cell culture, molecular biology, transgenic biology, microbiology, recombinant DNA, and immunology, which are within the skill of the art. Such techniques are explained fully in the literature. (See, for example, Sambrook *et al.*, ed. (1989) *Molecular Cloning A Laboratory Manual* (2nd ed.; Cold Spring Harbor Laboratory Press); Sambrook *et al.*, ed. (1992) *Molecular Cloning: A Laboratory Manual*, (Cold Springs Harbor Laboratory, NY); D. N. Glover ed., (1985) *DNA Cloning*, Volumes I and II; Gait, ed. (1984) *Oligonucleotide Synthesis*; Mullis *et al.* U.S. Pat. No. 4,683,195; Hames and Higgins, eds. (1984) *Nucleic Acid Hybridization*; Hames and Higgins, eds. (1984) *Transcription And Translation*; Freshney (1987) *Culture Of Animal Cells* (Alan R. Liss, Inc.); Immobilized Cells And Enzymes (IRL Press) (1986); Perbal (1984) *A Practical Guide To Molecular Cloning*; the treatise, *Methods In Enzymology* (Academic Press, Inc., N.Y.); Miller and Calos eds. (1987) *Gene Transfer Vectors For Mammalian Cells*, (Cold Spring Harbor Laboratory); Wu *et al.*, eds., *Methods In Enzymology*, Vols. 154 and 155; Mayer and Walker, eds. (1987) *Immunochemical Methods In Cell And Molecular Biology* (Academic Press, London); Weir and Blackwell, eds., (1986) *Handbook Of Experimental Immunology*, Volumes I-IV; *Manipulating the Mouse Embryo*, Cold Spring Harbor Laboratory Press, Cold Spring Harbor, N.Y., (1986); and in Ausubel *et al.* (1989) *Current Protocols in Molecular Biology* (John Wiley and Sons, Baltimore, Md.).

- [0136] General principles of antibody engineering are set forth in Borrebaeck, ed. (1995) *Antibody Engineering* (2nd ed.; Oxford Univ. Press). General principles of protein engineering are set forth in Rickwood *et al.*, eds. (1995) *Protein Engineering, A Practical Approach* (IRL Press at Oxford Univ. Press, Oxford, Eng.). General principles of antibodies and antibody-hapten binding are set forth in: Nisonoff (1984) *Molecular Immunology* (2nd ed.; Sinauer Associates, Sunderland, Mass.); and Steward (1984) *Antibodies, Their Structure and Function* (Chapman and Hall, New York, N.Y.). Additionally, standard methods in immunology known in the art and not specifically described can be followed as in *Current Protocols in Immunology*, John Wiley & Sons, New York; Stites *et al.*, eds. (1994) *Basic and Clinical Immunology* (8th ed; Appleton & Lange, Norwalk, Conn.) and Mishell and Shiigi (eds) (1980) *Selected Methods in Cellular Immunology* (W.H. Freeman and Co., NY).
- [0137] Standard reference works setting forth general principles of immunology include *Current Protocols in Immunology*, John Wiley & Sons, New York; Klein (1982) *J., Immunology: The Science of Self-Nonself Discrimination* (John Wiley & Sons, NY); Kennett *et al.*, eds. (1980) *Monoclonal Antibodies, Hybridoma: A New Dimension in Biological Analyses* (Plenum Press, NY); Campbell (1984) "Monoclonal Antibody Technology" in *Laboratory Techniques in Biochemistry and Molecular Biology*, ed. Burden *et al.*, (Elsevier, Amsterdam); Goldsby *et al.*, eds. (2000) *Kuby Immunology* (4th ed.; H. Freeman & Co.); Roitt *et al.* (2001) *Immunology* (6th ed.; London: Mosby); Abbas *et al.* (2005) *Cellular and Molecular Immunology* (5th ed.; Elsevier Health Sciences Division); Kontermann and Dubel (2001) *Antibody Engineering* (Springer Verlag); Sambrook and Russell (2001) *Molecular Cloning: A Laboratory Manual* (Cold Spring Harbor Press); Lewin (2003) *Genes VIII* (Prentice Hall, 2003); Harlow and Lane (1988) *Antibodies: A Laboratory Manual* (Cold Spring Harbor Press); Dieffenbach and Dveksler (2003) *PCR Primer* (Cold Spring Harbor Press).
- [0138] All of the references cited above, as well as all references cited herein, are incorporated herein by reference in their entireties. The following examples are offered by way of illustration and not by way of limitation.

Examples

Example 1: Fusion Protein Construction

[0139] IMPs were incorporated into vaccinia virus EEVs using the EEV-specific proteins F13L, A56R, and B5R, by the following methods. Generally, the extracellular domains of HER2, CD100 (semaphorin 4D), and FZD4 were incorporated as fusions with the single-pass EEV-specific membrane proteins A56R and B5R as diagrammed in **FIG. 1A**. The mature FZD4-ECD-A56R fusion protein comprises amino acids 20 to 370 of SEQ ID NO: 6, the mature HER2-ECD-A56R fusion protein comprises amino acids 20 to 855 of SEQ ID NO: 7, and the mature CD100-ECD-A56R fusion protein comprises amino acids 20 to 935 SEQ ID NO: 8. **FIG. 1B** and **FIG. 1C** show diagrammatically how the multi-pass proteins such as GPCRs and CD20 can be incorporated into EEVs as multi-pass membrane proteins as a fusion with the EEV membrane-associated protein F13L.

Preparation of F13L Fusion Proteins (FZD4-F13L, CD20-F13L, and CXCR4-F13L)

[0140] cDNAs encoding the IMPs were cloned in-frame to the vaccinia virus F13L gene encoding the palmitoylated EEV membrane glycoprotein (SEQ ID NO: 1) into the pJEM1 plasmid previously described for the purpose of introduction into vaccinia virus. pJEM1 is a derivative of p7.5/tk described in U.S. Patent Appl. Publ. No. 2013/0288927, and when digested with NcoI or BssHII and BsiWI, contains flanking regions capable of homologous recombination with the vaccinia virus TK gene and the vaccinia virus H5 promoter.

[0141] The open reading frame of human membrane protein MS4A1 gene (CD20)(NM_021950.3) was cloned in frame with the vaccinia virus F13L using SOE (Splicing by Overlap Extension) PCR as per standard protocols whereby restriction endonuclease sites NcoI and BsiWI were added to the PCR product by encoding them into the 5' and 3'-most flanking primers respectively. This strategy avoids the introduction of a leader peptide. The final PCR product and pJEM1 were digested with NcoI and BsiWI and the two species were joined via ligation according to standard protocols. The circularized plasmid was then introduced into competent *E. coli* via chemical transformation and colonies were selected on ampicillin-containing agar plates.

MS4A1S tata**CCATGg**CAACACCCAGAAATTCAGTAAATG (SEQ ID NO: 12)
GGTACCGATGCAAATGGCCACATAGGAGAGCTGTCATTTCTATTGG (SEQ
MS4A1AS ID NO: 13)

F13S CCAATAGAAAATGACAGCTCTCCTATGTGGCCATTTGCATCGGTACC (SEQ ID NO: 14)

F13AS tataCGTACGTTAATGGTGATGGTGATGATGAATTTTAACGATTACTGTG (SEQ ID NO: 15)

[0142] The resulting CD20-F13L fusion protein encoded by the polynucleotide comprises the amino acid sequence SEQ ID NO: 4.

[0143] The open reading frame of human membrane protein FZD4 (NM_012193.3) was cloned in frame with the vaccinia virus F13L using SOE (Splicing by Overlap Extension) PCR as per standard protocols whereby restriction endonuclease sites BssHII and BsiWI were added to the PCR product by encoding them into the 5' and 3'-most flanking primers, respectively. This strategy provides for the use of the leader peptide contained within pJEM1. The final PCR product and pJEM1 were digested with BssHII and BsiWI and the two species were joined via ligation according to the standard protocols. The circularized plasmid was then introduced into competent *E. coli* via chemical transformation and colonies were selected on ampicillin-containing agar plates. PCR primers were specific for FZD4 and F13L and conform to the same general strategy as described for MS4A1. The resulting mature FZD4-F13L fusion protein encoded by the polynucleotide comprises amino acids 20-892 of SEQ ID NO: 2.

[0144] The open reading frame of human membrane protein CXCR4 (NM_001008540.1) was cloned in frame with the vaccinia virus F13L using SOE (Splicing by Overlap Extension) PCR as per standard protocols whereby restriction endonuclease sites NcoI and BsiWI were added to the PCR product by encoding them into the 5' and 3'-most flanking primers respectively. This strategy avoids the introduction of a leader peptide. The final PCR product and pJEM1 were digested with NcoI and BsiWI and the two species were joined via ligation according to the standard protocol. The circularized plasmid was then introduced into competent *E. coli* via chemical transformation and colonies were selected on ampicillin-containing agar plates. PCR primers were specific for CXCR4 and F13L and conform to the same general strategy as described for MS4A1. The resulting CXCR4-F13L fusion protein encoded by the polynucleotide comprises the amino acid sequence SEQ ID NO: 3.

[0145] The plasmids produced as described above, as well as similar plasmids encoding non-fused ("untagged") versions of CD20, FZD4, CXCR4, CD100, and HER2, were linearized and introduced into vaccinia virus via tri-molecular recombination.

Example 2: Expression of CD20-F13L Fusion Protein on EEV

- [0146] BHK cells were infected with either IMV encoding the CD20-F13L fusion protein (SEQ ID NO: 4) or Control Western Reserve (WR) virus at a multiplicity of infection (MOI) of 1 virus per cell for two days after which the supernatant containing EEV was harvested and debris removed by low speed centrifugation. Protein G DYNABEADS® (110 µL) were pulled down with a magnet and 1 mL of PBS + 20 µg of purified anti-CD20 antibody was added to the beads. The solution was incubated at room temperature with gentle rotation for 30-60 minutes to allow the antibody to couple to the Protein G beads. Ten µg of purified mIgG1 isotype control was added to the solution to ensure complete blocking, and the solution was incubated at room temperature with gentle rotation for 10-30 additional minutes. Beads were pulled down with the magnet, washed once with 1 mL of PBS and resuspended in 110 µL of PBS.
- [0147] Fifty µL of Anti-CD20-Pro G DYNABEADS® was added to 1 mL of CD20-F13L or WR EEV supernatant and was incubated at room temperature with gentle rotation for 1 hour. Beads were pelleted using the magnet and unbound supernatant removed. The beads were then washed five times with 1 mL of Dulbecco's Modified Eagle Medium (DMEM) media supplemented with 10% FBS and 1 mM HEPES (10% DMEM). All washes were pooled with the unbound supernatant ("Unbound"). The beads ("Bound") were then resuspended in 1 mL of 10% DMEM. "Unbound" and "Bound" were titered on BSC-1 cells and overlaid with growth medium containing methylcellulose. Plaques were allowed to form for two days and then the cells were fixed and stained with 0.1% Crystal Violet solution. Plaques were counted to determine the number of plaque forming units (pfu) in the "Unbound" and "Bound" from which the % of EEV bound to the beads could be calculated. Results are shown on Table 2.

Table 2: CD20-F13L EEV Binding

EEV Supernatant	% Bound
Western Reserve	10.8 %
CD20-F13L	50.5%

- [0148] The % EEV bound to the anti-CD20 coated beads was significantly higher for CD20-F13L EEV fusion protein than it is for the Western Reserve indicating that CD20 is being expressed on the EEV membrane surface.

Example 3: Fusion of CD20 to F13L is more efficiently expressed on the EEV membrane

[0149] BHK cells were infected with either IMV encoding the CD20-F13L fusion protein (SEQ ID NO: 4), CD20-A56R fusion protein (SEQ ID NO: 13), CD20 untagged (unfused) or control HER2-A56R Extracellular Domain (ECD) (SEQ ID NO: 7) virus at an MOI=1 for two days after which the supernatant containing EEV was harvested and debris removed by low speed centrifugation. Streptavidin DYNABEADS® (200 µL) were pulled down with a magnet and 0.2 mL of PBS + 20 µg of purified Biotinylated anti-CD20 antibody or Biotinylated anti-HER2 was added to the beads. The solution was incubated at room temperature with gentle rotation for 30 minutes to allow the antibody to couple to the Streptavidin beads. Beads were pulled down with the magnet, washed once with 1 mL of PBS and resuspended in 200 µL of PBS.

CD20-A56R: (SEQ ID NO: 13)

MGWSCILFLVATATGAHTELIVNTDSESTIDILSGSTHSPETS
SKKPDYIDNSNCSSVFEIATPEPITDNVEDHTDVTYTSDSINTVS
ASSGESTTDETPETIDKEDHTVTDIVSYTIVSTSSGIVTTKSTTD
DADLYDTYNDNDTVPPTVGGSTTSISNYKTKDFVEIFGITALIIL
SAVAIFCITYYYINKRSRKYKTENKVMTTPRNSVNGTFPAEPM
KGPIAMQSGPKPLFRMSSLVGPTQSFFMRESKTLGAVQ
IMNGLFHIALGGLLMIPAGIYAPICVTVWYPLWGGIMYII
SGSLAATEKNSRKCLVKGKMIMNSLSLFAAISGMILSIM
DILNIKISHFLKMESLNFIRAHTPYINIYNCEPANPSEKNSP
STQYCYSIQSLFLGILSVMLIFAFFQELVIAGIVENEWKRT
CSRPKSNIVLLSAEEKKEQTIEIKEEVVGLTETSSQPKNE
EDIEIPIQEEEEETETNFPPEPPQDQESSPIENDSSP

Single Underline – Signal sequence (amino acids 1-19)

Italics – Truncated A56R (amino acids 20-190)

Bold – CD20 Sequence (amino acids 191-506)

[0150] Fifty µL of prepared streptavidin beads were added to 1 mL of each EEV supernatant and allowed to rotate at room temperature for 45 minutes. Beads were pelleted using the magnet and unbound supernatant removed. The beads were then washed five times with 1 mL of DMEM media supplemented with 10% FBS and 1 mM HEPES (10% DMEM). All washes were pooled with the unbound supernatant (“Unbound”). The beads (“Bound”) were then resuspended in 1 mL of 10% DMEM. “Unbound” and “Bound” were titrated on BSC-1

cells and overlaid with growth medium containing methylcellulose. Plaques were allowed to form for two days and then the cells were fixed and stained with 0.1% Crystal Violet solution. Plaques were counted to determine the number of plaque forming units (pfu) in the “Unbound” and “Bound” from which the % of EEV bound to the beads could be calculated. Results are shown in **FIG. 2**.

[0151] The % EEV bound to the anti-CD20 coated beads for CD20-F13L was greater than the % EEV bound for untagged (unfused) or A56R-fused CD20 indicating higher expression of CD20-F13L on the EEV membrane. The lack of binding to the anti-HER2 coated beads confirmed specificity of the assay.

[0152] The experiment above was repeated using CD20-F13L fusion protein (SEQ ID NO: 4), CD20 untagged (unfused), FZD-F13L fusion protein (SEQ ID NO: 2), and FZD untagged (unfused). Virus was pulled down using anti-CD20 or anti-FZD coated beads as described above. The data in **FIG. 3A** (anti-CD20-coated beads) and **FIG. 3B** (anti-FZD-coated beads) shows that F13L fusion proteins were specifically pulled down by their respective antibodies, and were more efficiently incorporated into vaccinia virus than untagged (unfused) proteins.

Example 4: Vaccinia Virus can be engineered to express various antigen-EEV constructs

[0153] BHK cells were infected at an MOI=1 with virus expressing the following antigen constructs: CD20-F13L (SEQ ID NO: 4), CXCR4-F13L (SEQ ID NO: 3), HER2-ECD-A56R (SEQ ID NO: 7), and CD100-ECD-A56R (SEQ ID NO: 8). After two days, the supernatant containing EEV was harvested and debris removed by low speed centrifugation. Streptavidin DYNABEADS® were pulled down with a magnet and for each sample, 50 µL of beads were resuspended in 0.1 mL of PBS + 5 µg of purified Biotinylated anti-CD20 antibody, Biotinylated anti-CXCR4 (12G5), Biotinylated anti-CD100 (2503), or Biotinylated anti-HER2. The solutions were incubated at room temperature with gentle rotation for 30 minutes to allow the antibody to couple to the Streptavidin beads. Beads were pulled down with the magnet, washed once with 1 mL of PBS and resuspended in 100 µL of PBS per sample.

[0154] One hundred µL of prepared streptavidin beads were added to 1 mL of each EEV supernatant and allowed to rotate at room temperature for 45 minutes. Beads were pelleted

using the magnet and unbound supernatant removed. The beads were then washed five times with 1 mL of DMEM media supplemented with 10% FBS and 1 mM HEPES (10% DMEM). All washes were pooled with the unbound supernatant ("Unbound"). The beads ("Bound") were then resuspended in 1 mL of 10% DMEM. "Unbound" and "Bound" were titered on BSC-1 cells and overlaid with growth medium containing methylcellulose. Plaques were allowed to form for two days and then the cells were fixed and stained with 0.1% Crystal Violet solution. Plaques were counted to determine the number of plaque forming units (pfu) in the "Unbound" and "Bound" from which the % of EEV bound to the beads could be calculated. Results are shown in **FIG. 4**.

[0155] All of the antigen-EEV bound specifically to their corresponding antibody-coupled beads indicating efficient expression of the antigen on the EEV membrane.

Example 5: Antigen-EEV can be directly coupled to magnetic beads for antibody selection

[0156] BHK cells (2×10^8 cells) were infected at an MOI=1 with virus expressing HER2-ECD-A56R (SEQ ID NO: 7), FZD-F13L (SEQ ID NO: 2), CXCR4-F13L (SEQ ID NO: 3) or CD100 (semaphorin 4D)-ECD-A56R (SEQ ID NO: 8) in one cellSTACK cell culture chamber each (Corning). After two days, the supernatant containing EEV was harvested and debris removed by low speed centrifugation. The clarified supernatant was then spun at 13,000 rpm (28,000 x g) for 1 hour to pellet the antigen-EEV. The supernatant was aspirated and the pellet resuspended in 1.5 mL of 1X PBS. The various viruses were transferred to fresh tubes and Psoralen (Trioxsalen, 4'-aminomethyl-, hydrochloride; Sigma) was added to 20 µg/ml final concentration. The EEV and Psoralen were incubated at room temperature for 10 minutes before being irradiated in the STRATALINKER® UV Crosslinker (Stratagene) for 99,999 microjoules. The Psoralen/UV procedure ensures that the antigen-EEV is inactivated and therefore unable to form plaques or multiply in any downstream testing.

[0157] Tosylactivated MyOne DYNABEADS® (100 µL) were pulled down with a magnet and washed with 1 mL of PBS. The beads were pulled down with the magnet, the PBS removed and 1 mL of each Psoralen/UV inactivated antigen-EEV was added to a separate aliquot of beads. The beads and antigen-EEV were allowed to rotate at 37 °C for 16-20 hours. The beads were pelleted and the supernatant was removed. The beads were blocked

with 1 mL of 1X PBS, 10% FBS and 0.5% BSA at 37 °C for 1 hour. The beads were pelleted and washed with 1 mL 1X PBS before being resuspended in 200 µL of 1X PBS.

[0158] One hundred microliters of antigen-EEV-coupled beads was added to 1 mL of each respective antibody-EEV supernatant expressing anti-FZD4, anti-CXCR4, anti-CD100, or anti-HER2, as well as to control antibody-EEV. Antibody EEV were produced by infecting BHK cells at an MOI=1 each for 2 days with vaccinia virus encoding both the heavy and light chains of the respective antibodies, and harvesting the supernatants followed by a low speed spin to remove any cells. The virus coupled beads and antibody EEV were allowed to rotate at room temperature for 2 hours. Beads were pelleted using the magnet and unbound supernatants removed. The beads were then washed five times with 1 mL of DMEM media supplemented with 10% FBS and 1 mM HEPES (10% DMEM). All washes were pooled with the unbound supernatant (“Unbound”). The beads (“Bound”) were then resuspended in 1 mL of 10% DMEM. “Unbound” and “Bound” were titered on BSC-1 cells and overlaid with growth medium containing methylcellulose. Plaques were allowed to form for two days and then the cells were fixed and stained with 0.1% Crystal Violet solution. Plaques were counted to determine the number of plaque forming units (pfu) in the “Unbound” and “Bound” from which the % of EEV bound to the beads could be calculated. A diagram of the method is shown in **FIG 5**, and results are shown in **FIG. 6A** (HER2), **FIG. 6B** (FZD4), **FIG. 6C** (CXCR4), and **FIG. 6D** (CD100 (“Sema”)).

[0159] Antibody-EEV expressing Anti-HER2 was specifically pulled down by beads coupled with HER2-ECD-A56R antigen EEV, Antibody-EEV expressing Anti-FZD was specifically pulled down by beads coupled with FZD-F13L antigen EEV, Antibody-EEV expressing Anti-CXCR4 was specifically pulled down by beads coupled with CXCR4-F13L antigen EEV, and Antibody-EEV expressing Anti-SEMA was specifically pulled down by beads coupled with Sema-ECD-A56R antigen EEV.

Example 6: Antibody Library Screening

[0160] BHK cells were infected at an MOI=1 each with an antibody library (H-IgG-A56R) and L48 (derivative of germline VK1-39) in four cellSTACK cell culture chamber (Corning) (2 x 10⁸ cells per stacker). The antibody library contained a diverse population of heavy chain variable domains in full length IgG format, fused in frame to A56R (see US Patent Appl. Publication No. 2013-0288927, which is incorporated herein by reference in its

entirety). The diversity of this library was approximately 400 million independent clones. After two days, the supernatant containing EEV was harvested and debris removed by low speed centrifugation. The clarified supernatant was then spun at 13,000 rpm (28,000 x g) for 1 hour to pellet the antibody-EEV. The antibody-EEV was resuspended in 1ml EMEM with 10% FBS and stored at 4 degrees until ready for use. In order to make the antigen virus for panning, BHK cells (2×10^8 cells) were infected at an MOI=1.5 with virus expressing FZD4-ECD-A56R (SEQ ID NO: 6) in two cellSTACK cell culture chamber (Corning). After two days, the supernatant containing EEV was harvested and debris removed by low speed centrifugation. The clarified supernatant was then spun at 13,000 rpm (28,000 x g) for 1 hour to pellet the antigen-EEV. The supernatant was aspirated and the pellet resuspended in 1.0 mL of 1X PBS. The one mL of the FZD4-ECD-A56R EEV was transferred to a fresh tube and Psoralen (Trioxsalen, 4'-aminomethyl-, hydrochloride; Sigma) was added to 40 µg/ml final concentration. The EEV and Psoralen were incubated at room temperature for 10 minutes before being irradiated in the STRATALINKER® UV Crosslinker (Stratagene) for 99,999 microjoules. The Psoralen/UV procedure ensures that the antigen-EEV is inactivated and therefore unable to form plaques or multiply in any downstream testing.

[0161] Tosylactivated MyOne DYNABEADS® (150 µL) were pulled down with a magnet and washed with 1 mL of PBS, two times. The beads were pulled down with the magnet, the PBS removed and the 1 mL of Psoralen/UV inactivated FZD4-ECD-A56R was added to the beads. The beads and antigen-EEV were allowed to rotate at 37 °C for 18-20 hours. The beads were pelleted and the supernatant was removed. The beads were blocked with 1 mL of 1X PBS, 10% FBS and 0.5% BSA at 37 °C for 2 hours. The beads were pelleted and washed with 1 mL 1X PBS before being resuspended in 150 µL of 1X PBS.

[0162] Fifty microliters of FZD4-ECD-A56R-coupled beads were added to 1 mL of the antibody-EEV library. The FZD4-ECD-A56R coupled beads and antibody EEV were allowed to rotate at room temperature for 2 hours. Beads were pelleted using the magnet and unbound supernatant removed. The beads were then washed five times with 1 mL of DMEM media supplemented with 10% FBS and 1 mM HEPES (10% DMEM). All washes were pooled with the unbound supernatant ("Unbound"). The beads ("Bound") were then resuspended in 1 mL of 10% DMEM. "Unbound" and "Bound" were titered on BSC-1 cells and overlaid with growth medium containing methylcellulose. Plaques were allowed to form for two days and then the cells were fixed and stained with 0.1% Crystal Violet solution. The

remaining bound virus (990 μ l) was divided among 5 T175 flasks containing confluent BSC1 cells and allowed to amplify in DMEM2.5% containing 1mg/ml G418 for 3 days. The cells were then harvested, and the virus released by three cycles of freeze/thaw, and the virus titered.

[0163] For the second round of selection (Rd2), the amplified Heavy chains from round 1 were co-infected along with fresh L48 into one cellSTACK of BHK. Antibody EEV was harvested as described above. For each round of panning, fresh FZD-ECD-A56R antigen virus was produced, concentrated, inactivated and coupled to beads as described above. Fifty microliters of FZD4-ECD-A56R coupled beads was added to 1 mL antibody-EEV Rd2. The FZD4-ECD-A56R coupled beads and antibody EEV were allowed to rotate at room temperature for 2 hours. Beads were pelleted using the magnet and unbound supernatant removed. The beads were then washed five times with 1 mL of DMEM media supplemented with 10% FBS and 1 mM HEPES (10% DMEM). All washes were pooled with the unbound supernatant ("Unbound"). The beads ("Bound") were then resuspended in 1 mL of 10% DMEM. "Unbound" and "Bound" were titered on BSC-1 cells and overlaid with growth medium containing methylcellulose. Plaques were allowed to form for two days and then the cells were fixed and stained with 0.1% Crystal Violet solution. The remaining bound virus (990 μ l) was divided among 5 T175 flasks containing confluent BSC1 cells and allowed to amplify in DMEM2.5% containing 1mg/ml G418 for 3 days. The cells were then harvested, and the virus released by three cycles of freeze/thaw, and the virus titered.

[0164] Three additional cycles of panning (Rd3, Rd4, and Rd5) were performed as described above.

[0165] Rounds 3, 4 and 5 were tested for enrichment by infected A431 cells in 6 well plate at moi = 1 with each amplified VH round and L48. After an overnight infection the cells were harvested and split in half. One half was stained with 10 μ g/ml FZD-His, followed by anti-His-Dyelight650 and anti-Fab-FITC. The other half was stained with 10 μ g/ml CD100-His (negative control), followed by anti-His-Dyelight650 and anti-Fab-FITC. The data shown in **FIG 7** shows increasing enrichment per round of selection. Antibodies from round 5 were sub-cloned into a mammalian expression vector to be expressed as full length soluble IgG and transfected (along with L48 in a mammalian expression vector). The resulting antibodies present in the supernatant were tested by flow cytometry for binding to FZD4

transfected CHO cells and the absence of binding to CXCR4 transfected CHO cells. A number of antibodies that bound specifically to FZD were identified.

Example 7: Dual Tag/Antigen EEV can be Coupled to Magnetic Beads

[0166] BHK cells were infected at two virions per cell where one virion was Hemagglutinin tag (HA)-A56R (SEQ ID NO: 14) and the second was FZD4-F13L (SEQ ID NO: 2) in order to yield EEV expressing both the HA tag and FZD4 antigen on its surface or infected at one virion per cell with each individual virus. After two days, the supernatant containing EEV was harvested and debris removed by low speed centrifugation. Protein G magnetic beads (150 μ L) were pulled down with a magnet and 1 mL of PBS + 30 μ g of purified anti-FZD4 antibody (C6073) was added to the beads. The solution was incubated at room temperature with gentle rotation for 25 minutes to allow the antibody to couple to the Protein G beads. Beads were pulled down with the magnet, washed once with 1 mL of PBS and resuspended in 300 μ L of DMEM + 10% FBS. Anti-HA-tag magnetic beads (ThermoFisher, 150 μ L) pulled down with a magnet and washed once with 1 mL of PBS before resuspending in 150 μ L of PBS.

HA-A56R (SEQ ID NO: 14)

MGWSCILFLVATATGAHS**YPYDVPDYAT***STTNDTDKVDYEEYS*
TELIVNTDSESTIDIILSGSTHSPETSSKKPDYIDNSNCSSVFEIATP
EPITDNVEDHTDVTYTSDSINTVSASSGESTTDETPEPITDKED
HVTDTVSYTTVSTSSGIVTTKSTTDDADLYDTYNDNDTVPPTTV
GGSTTSISNYKTKDFVEIFGITALIILSAVAIFCITYYYINKRSRKYK
TENKV

Single Underline – Signal sequence (amino acids 1-19)

Bold – HA Tag (amino acids 20-29)

Italics – Truncated A56R (amino acids 30-235)

[0167] Fifty μ L of prepared anti-HA-tag beads or 100 μ L of prepared anti-FZD4 Protein G were added to 1 mL of each EEV supernatant and allowed to rotate at room temperature for 60 minutes. Beads were pelleted using the magnet and unbound supernatant removed. The beads were then washed five times with 1 mL of DMEM media supplemented with 10% FBS and 1 mM HEPES (10% DMEM). All washes were pooled with the unbound supernatant (“Unbound”). The beads (“Bound”) were then resuspended in 1 mL of 10% DMEM. “Unbound” and “Bound” were titered on BSC-1 cells and overlaid with growth

medium containing methylcellulose. Plaques were allowed to form for two days and then the cells were fixed and stained with 0.1% Crystal Violet solution. Plaques were counted to determine the number of plaque forming units (pfu) in the “Unbound” and “Bound” from which the % of EEV bound to the beads could be calculated. Results are shown in **FIG 8**. EEV expressing both fusion proteins were pulled down by either antibody.

Example 8: Dual Tag/Antigen EEV can be Coupled to Magnetic Beads and used to Capture mAb EEV

- [0168] BHK cells (2×10^8 cells) were infected at two virions per cell where one virion was HA-A56R (SEQ ID NO: 14) and the second was CXCR4-F13L (SEQ ID NO: 3) in order to yield EEV expressing both the HA tag and CXCR4 antigen on its surface. After two days, the supernatant containing EEV was harvested and debris removed by low speed centrifugation. The clarified supernatant was then spun at 13,000 rpm (28,000xg) for 1 hour to pellet the tag/antigen-EEV. The supernatant was aspirated and the pellet resuspended in 1 mL of 1X PBS. Psoralen (Trioxsalen, 4'-aminomethyl-, hydrochloride; Sigma) was added to 40 ug/ml final concentration. The EEV and Psoralen were incubated at room temperature for 10 minutes before being irradiated in the Stratalink UV Crosslinker (Stratagene) for 99,999 microjoules twice. The Psoralen/UV procedure ensures that the antigen-EEV is inactivated and therefore unable to form plaques or multiply in any downstream testing.
- [0169] Anti-CXCR4 EEV and anti-HER2 mAb EEV were produced by infecting BHK cells at two virions per cell where one virion was specific heavy chain and the second was specific light chain. After two days, supernatants containing the anti-CXCR4 EEV and the anti-HER2 EEV were harvested and debris removed by low speed centrifugation.
- [0170] Three hundred microliters of anti-HA magnetic beads were washed with 1 mL of PBS and then resuspended in one milliliter of the Psoralen/UV inactivated HA/CXCR4 EEV. The beads and EEV were incubated at room temperature with gentle rotation for 90 minutes to allow the EEV to couple with the anti-HA beads. Beads were pulled down with the magnet, washed once with 1 mL of PBS and resuspended in 300 μ L of PBS.
- [0171] One hundred μ L of HA/CXCR4 EEV coupled to the anti-HA beads was added to 1 mL of each mAb EEV supernatant and incubated at room temperature with gentle rotation for 1-1.5 hours. Beads were pelleted using the magnet and unbound supernatant removed. The beads were then washed five times with 1 mL of DMEM media supplemented with 10%

FBS and 1 mM HEPES (10% DMEM). All washes were pooled with the unbound supernatant ("Unbound"). The beads ("Bound") were then resuspended in 1 mL of 10% DMEM. "Unbound" and "Bound" were titrated on BSC-1 cells and overlaid with growth medium containing methylcellulose. Plaques were allowed to form for two days and then the cells were fixed and stained with 0.1% Crystal Violet solution. Plaques were counted to determine the number of plaque forming units (pfu) in the "Unbound" and "Bound" from which the % of EEV bound to the beads could be calculated. Results are shown in **FIG 9**. Anti-CXCR4 EEV were specifically captured by the beads coated with EEV co-expressing HA-A45R and CXCR4-F13L.

Example 9: Antigen-EEV can be biotinylated for coupling to magnetic beads

[0172] BHK cells were infected at an MOI=1 with virus expressing FZD4-F13L, FZD4-ECD-A56R or CD20-F13L. After two days, the supernatant containing EEV was harvested and debris removed by low speed centrifugation. The clarified supernatant was then spun at 13,000 rpm for 1 hour to pellet the antigen-EEV. The supernatant was aspirated and the pellet resuspended in 1-2 mL of 1X PBS. To biotinylate the EEV, 2.5 μ L of Biotin-XX SSE stock solution in 1X PBS (FLUOREPORTER® Cell Surface Biotinylation Kit, Molecular Probes) was added to the 1 mL of each EEV in PBS and incubated on ice for 30 minutes. Fifty μ L of 1M Tris, pH 8 was added to quench each reaction.

[0173] To couple the Biotin-EEV to beads, 150 μ L of Streptavidin DYNABEADS® were pelleted and washed once with 1 mL of 1X PBS. The beads were resuspended in 150 μ L and 50 μ L was added to 1 mL of Eagle's Minimum Essential Medium (EMEM) media containing 10% FBS and 1 mM HEPES (10% EMEM). Fifty μ L of Biotin-EEV was added to the beads and media and allowed to rotate at room temperature for 1 hour. Beads were pelleted using the magnet and unbound supernatant removed. The beads were then washed five times with 1 mL of DMEM media supplemented with 10% FBS and 1 mM HEPES (10% DMEM). All washes were pooled with the unbound supernatant ("Unbound"). The beads ("Bound") were then resuspended in 1 mL of 10% DMEM. "Unbound" and "Bound" were titrated on BSC-1 cells and overlaid with growth medium containing methylcellulose. Plaques were allowed to form for two days and then the cells were fixed and stained with 0.1% Crystal Violet solution. Plaques were counted to determine the number of plaque

forming units (pfu) in the “Unbound” and “Bound” from which the % of EEV bound to the beads could be calculated. Results are shown in **FIG. 10**.

[0174] Antigen-EEV was able to be biotinylated and coupled to magnetic Streptavidin beads.

WHAT IS CLAIMED IS:

1. An isolated polynucleotide comprising:

(a) a first nucleic acid fragment that encodes an integral membrane protein (IMP) or fragment thereof, wherein the IMP or fragment thereof comprises at least one extra-membrane region, at least one transmembrane domain and at least one intra-membrane region, and wherein a portion of the first nucleic acid fragment encoding at least one intra-membrane region is situated at the 5' or 3' end of the first nucleic acid fragment; and

(b) a second nucleic acid fragment that encodes a vaccinia virus F13L protein or functional fragment thereof, wherein the second nucleic acid fragment is fused in frame to a portion of the first nucleic acid fragment that encodes an intra-membrane region of the IMP;

wherein a poxvirus infected cell comprising the polynucleotide can express an IMP-F13L fusion protein as part of the outer envelope membrane of an extracellular enveloped virion (EEV).

2. The polynucleotide of claim 1, wherein the F13L protein or functional fragment thereof comprises the amino acid sequence SEQ ID NO: 1 or a functional fragment thereof.

3. The polynucleotide of claim 1 or claim 2, wherein the IMP is a multi-pass membrane protein comprising at least two, at least three, at least four, at least five, at least six or at least seven transmembrane domains.

4. The polynucleotide of claim 3, wherein the IMP has an odd number of transmembrane domains, wherein the 5' end of the first nucleic acid fragment encodes an extra-membrane region, wherein the 3' end of the first nucleic acid fragment encodes an intra-membrane region, and wherein the 5' end of the second polynucleotide is fused to the 3' end of the first nucleic acid fragment.

5. The polynucleotide of claim 4, wherein the IMP comprises a G-protein coupled receptor (GPCR).

6. The polynucleotide of claim 5, wherein the IMP is the human frizzled-4 protein (FZD4), or a fragment thereof.
7. The polynucleotide of claim 6, which encodes a polypeptide comprising amino acids 20 to 892 of SEQ ID NO: 2.
8. The polynucleotide of claim 7, further comprising a signal peptide.
9. The polynucleotide of claim 8, wherein the signal peptide comprises amino acids 1 to 19 of SEQ ID NO: 2.
10. The polynucleotide of claim 5, wherein the IMP is a CXC chemokine receptor.
11. The polynucleotide of claim 10, wherein the CXC chemokine receptor is CXCR4, or a fragment thereof.
12. The polynucleotide of claim 11, which encodes a polypeptide comprising the amino acid sequence SEQ ID NO: 3.
13. The polynucleotide of claim 3, wherein the IMP has an even number of transmembrane domains, and wherein both the 5' and 3' ends of the first nucleic acid fragment encode intra-membrane regions.
14. The polynucleotide of claim 13, wherein the second nucleic acid fragment is fused to 3' end of the first nucleic acid fragment.
15. The polynucleotide of claim 14, wherein the IMP is human CD20 protein, or a fragment thereof.
16. The polynucleotide of claim 15, which encodes a protein comprising the amino acid sequence SEQ ID NO: 4.
17. The polynucleotide of any one of claims 1 to 16, wherein the first and second nucleic acid fragments are directly fused.
18. The polynucleotide of any one of claims 1 to 17, further comprising a third nucleic acid fragment encoding a heterologous peptide.
19. The polynucleotide of claim 18, wherein the heterologous peptide comprises a linker sequence, an amino acid tag or label, or a peptide or polypeptide sequence that facilitates purification.

20. The polynucleotide of claim 19, wherein the heterologous peptide comprises a histidine tag.

21. The polynucleotide of any one of claims 1 to 20, which is operably associated with a poxvirus promoter.

22. The polynucleotide of claim 21, wherein the poxvirus promoter is p7.5 or H5 or T7.

23. The F13L fusion protein encoded by the polynucleotide of any one of claims 1 to 22.

24. A poxvirus genome comprising the polynucleotide of any one of claims 1 to 22.

25. The poxvirus genome of claim 24, which is a vaccinia virus genome.

26. A recombinant vaccinia virus EEV comprising the poxvirus genome of claim 25.

27. A method of producing the recombinant vaccinia virus EEV of claim 26, comprising:

- (a) infecting a host cell permissive for vaccinia virus infectivity with a vaccinia virus comprising the poxvirus genome of claim 24, and
- (b) recovering EEV released from the host cell.

28. A method to display an integral membrane protein (IMP) or fragment thereof in a native conformation comprising:

- (a) infecting host cells permissive for poxvirus infectivity with a recombinant poxvirus that expresses the IMP or fragment thereof as a fusion protein with poxvirus EEV-specific protein or membrane-associated fragment thereof, wherein EEV produced by the infected host cell comprise the IMP fusion protein as part of the EEV outer envelope membrane;
- (b) recovering EEV released from the host cell

wherein the IMP or fragment thereof displays on the surface of the EEV in a native conformation.

29. The method of claim 28, wherein the EEV-specific protein is the vaccinia virus A33R protein, A34R protein, A56R protein, B5R protein, A36R protein, F13L protein, any membrane-associated fragment thereof, or any combination thereof.

30. The method of claim 29, wherein the EEV-specific protein is F13L (SEQ ID NO: 1) or a functional fragment thereof.

31. The method of claim 30, wherein the IMP is a multi-pass membrane protein comprising at least two, at least three, at least four, at least five, at least six or at least seven transmembrane domains.

32. The method of claim 31, wherein the IMP comprises a G-protein coupled receptor (GPCR) comprising seven transmembrane domains, and wherein F13L is fused to the C-terminus of the IMP.

33. The method of claim 32, wherein the IMP is the human frizzled-4 protein (FZD4), or a fragment thereof.

34. The method of claim 33, wherein the fusion protein comprises amino acids 20 to 892 of SEQ ID NO: 2.

35. The method of claim 34, wherein the fusion protein further comprises a signal peptide.

36. The method of claim 35, wherein the signal peptide comprises amino acids 1 to 19 of SEQ ID NO: 2.

37. The method of claim 32, wherein the IMP is a CXC chemokine receptor.

38. The method of claim 37, wherein the CXC chemokine receptor is CXCR4, or a fragment thereof.

39. The method of claim 38, wherein the fusion protein comprises the amino acid sequence SEQ ID NO: 3.

40. The method of claim 31, wherein the IMP or fragment thereof has an even number of transmembrane domains, and wherein both the N-terminus and the C-terminus of the IMP or fragment thereof are intra-membrane.

41. The method of claim 40, wherein F13L is fused to the C-terminus of the IMP.

42. The method of claim 41, wherein the IMP is human CD20, or a fragment thereof.

43. The method of claim 42, wherein the fusion protein comprises the amino acid sequence SEQ ID NO: 4.

44. The method of claim 29, wherein the membrane-associated EEV specific protein fragment comprises the stalk, transmembrane, and intra-membrane domains of the vaccinia virus A56R protein.

45. The method of claim 30, wherein the membrane-associated EEV specific protein fragment consists essentially of amino acids 108 to 314 of SEQ ID NO: 5.

46. The method of claim 45, wherein the IMP comprises the extracellular domain of human FZD4.

47. The method of claim 46, wherein the fusion protein comprises amino acids 20 to 370 of SEQ ID NO: 6.

48. The method of claim 46, wherein the fusion protein further comprises a signal peptide.

49. The method of claim 48, wherein the signal peptide comprises amino acids 1 to 19 of SEQ ID NO: 6.

50. The method of claim 45, wherein the IMP comprises the extracellular domain of human ErbB2 (Her2).

51. The method of claim 50, wherein the fusion protein comprises amino acids 20 to 855 of SEQ ID NO: 7.

52. The method of claim 51, wherein the fusion protein further comprises a signal peptide.

53. The method of claim 52, wherein the signal peptide comprises amino acids 1 to 19 of SEQ ID NO: 7.

54. The method of claim 45, wherein the IMP comprises the extracellular domain of human CD100 (Semaphorin 4D).

55. The method of claim 54, wherein the fusion protein comprises amino acids 20 to 935 of SEQ ID NO: 8.

56. The method of claim 55, wherein the fusion protein further comprises a signal peptide.

57. The method of claim 56, wherein the signal peptide comprises amino acids 1 to 19 of SEQ ID NO: 8.

58. The method of claim 29, wherein the membrane-associated EEV specific protein fragment comprises the transmembrane and intra-membrane domains of the vaccinia virus B5R protein.

59. The method of claim 58, wherein the membrane-associated EEV specific protein fragment consists essentially of amino acids 276 to 317 of SEQ ID NO: 9.

60. The method of claim 58, wherein the membrane-associated EEV specific protein fragment comprises the stalk, the transmembrane domain, and intra-membrane domain of the vaccinia virus B5R protein.

61. The method of claim 30, wherein the membrane-associated EEV specific protein fragment consists essentially of amino acids 238 to 317 of SEQ ID NO: 9.

62. The method of claim 59 or claim 61, wherein the IMP comprises the extracellular domain of human FZD4.

63. The method of claim 62, wherein the fusion protein comprises amino acids 20 to 243 of SEQ ID NO: 10 or amino acids 20 to 281 of SEQ ID NO: 11.

64. The method of claim 63, wherein the fusion protein further comprises a signal peptide.

65. The method of claim 64, wherein the signal peptide comprises amino acids 1 to 19 of SEQ ID NO: 10.

66. A fusion protein comprising:

- (a) amino acids 20 to 892 of SEQ ID NO: 2;
- (b) SEQ ID NO: 3;
- (c) SEQ ID NO: 4;
- (d) amino acids 20 to 370 of SEQ ID NO: 6;
- (e) amino acids 20 to 855 of SEQ ID NO: 7;
- (f) amino acids 20 to 935 of SEQ ID NO: 8;

- (g) amino acids 20 to 243 of SEQ ID NO: 10; or
- (h) amino acids 20 to 281 of SEQ ID NO: 11;

wherein the fusion protein, when expressed by a recombinant poxvirus, appears on the surface of a poxvirus extracellular enveloped virion (EEV) in a native conformation.

67. A recombinant poxvirus EEV comprising the fusion protein of claim 66.

68. A recombinant poxvirus EEV comprising a heterologous IMP or fragment thereof fused to a poxvirus EEV-specific protein or membrane-associated fragment thereof, wherein the fusion protein is situated in the EEV outer envelope membrane, wherein the IMP or fragment thereof displays on the surface of the EEV in its native conformation.

69. The recombinant poxvirus EEV of claim 67 or claim 68, wherein the poxvirus EEV is a vaccinia virus EEV

70. A method to select antibodies that bind to a multi-pass membrane protein comprising:

- (a) attaching the recombinant EEV of any one of claims 26, or 67 to 69 to a solid support;
- (b) providing an antibody display library, wherein the library comprises display packages displaying a plurality of antigen binding domains;
- (c) contacting the display library with the EEV such that display packages displaying antigen binding domains that specifically binds to the IMP expressed on the EEV can bind thereto;
- (d) removing unbound display packages; and
- (e) recovering display packages that display an antigen binding domain specific for the IMP expressed on the EEV.

71. The method of claim 70 wherein the recombinant EEV are inactivated prior to attachment to the solid support.

72. The method of claim 71, wherein the EEV are inactivated by incubation with Psoralen (Trioxsalen, 4'-aminomethyl-, hydrochloride) in the presence of UV irradiation.

73. The method of any one of claims 70 to 72, wherein the EEV are attached to the solid surface via reaction with tosyl groups attached to the surface.

74. The method of claim 73, wherein the solid surface is tosyl-activated magnetic beads.

75. The method of any one of claims 70 to 72, wherein the EEV are biotinylated and attached to a streptavidin coated solid surface.

76. The method of claim 75, wherein the solid surface is streptavidin-coated magnetic beads.