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ADENO-ASSOCIATED VIRUS VIRIONS WITH VARIANT CAPSID AND METHODS OF USE THEREOF

CROSS-REFERENCE

[0001] This application claims the benefit of U.S. Provisional Patent Application No. 61/478,355, filed April 22, 2011, which application is incorporated herein by reference in its entirety.

STATEMENT REGARDING FEDERALLY SPONSORED RESEARCH

[0002] This invention was made with government support under Grant Nos. EY016994-02 and EY1018241 awarded by the National Eye Institute of the National Institutes of Health. The government has certain rights in the invention.

BACKGROUND

[0003] Photoreceptors are the first neurons in the retina to receive and process visual information, converting visible electromagnetic radiation into hyperpolarized responses through phototransduction. The overwhelming majority of inherited retinal diseases result in the loss of these cells, either directly, such as in dominant mutations that affect rhodopsin protein folding, or indirectly, such as in recessive mutations that affect retinal recycling pathways in the retinal pigment epithelium (RPE).

[0004] AAV belongs to the *Parvoviridae* family and Dependovirus genus, whose members require co-infection with a helper virus such as adenovirus to promote replication, and AAV establishes a latent infection in the absence of a helper. Virions are composed of a 25 nm icosahedral capsid encompassing a 4.9 kb single-stranded DNA genome with two open reading frames: *rep* and *cap*. The non-structural *rep* gene encodes four regulatory proteins essential for viral replication, whereas *cap* encodes three structural proteins (VP1–3) that assemble into a 60-mer capsid shell. This viral capsid mediates the ability of AAV vectors to overcome many of the biological barriers of viral transduction–including cell surface receptor binding, endocytosis, intracellular trafficking, and unpackaging in the nucleus.

Literature

[0005] U.S. Patent Publication No. 2005/0053922; U.S. Patent Publication No. 2009/0202490; Allocca et al. (2007) *J. Virol.* 81:11372; Boucas et al. (2009) *J. Gene Med.* 11:1103.

SUMMARY

[0006] The present disclosure provides adeno-associated virus (AAV) virions with altered capsid protein, where the AAV virions exhibit greater infectivity of a retinal cell, when administered via intravitreal injection, compared to wild-type AAV. The present disclosure further provides methods of delivering a gene product to a retinal cell in an individual, and methods of treating ocular disease.

[0006a] In one aspect, there is provided a recombinant adeno-associated virus (rAAV) virion comprising:

a) a variant AAV capsid protein, wherein the variant AAV capsid protein comprises a peptide insertion relative to a corresponding parental AAV capsid protein, wherein the insertion site is located between two adjacent amino acids at a position between amino acids 570 and 611 of VP1 of AAV2 or the corresponding position in the capsid protein of another AAV serotype, wherein the peptide insertion is a peptide of Formula I, Formula IIa, Formula IIb, Formula III, or Formula IV, and wherein the AAV variant capsid protein confers increased infectivity of a retinal cell compared to the infectivity of the retinal cell by an AAV virion comprising the corresponding parental AAV capsid protein, wherein:

i) Formula I is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu, Asn, and Lys;

X2 is selected from Gly, Glu, Ala, and Asp;

X3 is selected from Glu, Thr, Gly, and Pro;

X4 is selected from Thr, Ile, Gln, and Lys;

X5 is selected from Thr and Ala;

X6 is selected from Arg, Asn, and Thr; and

X7, if present, is selected from Pro and Asn;

ii) Formula IIa is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

each of X1 – X4 is any amino acid;

X5 is Thr;

X6 is Arg; and

X7 is Pro;

iii) Formula IIb is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu and Asn;

X2, if present, is selected from Gly and Glu;

X3 is selected from Glu and Thr;

X4 is selected from Thr and Ile;

X5 is Thr;

X6 is Arg; and

X7 is Pro;

iv) Formula III is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is Lys;

X2 is selected from Ala and Asp;

X3 is selected from Gly and Pro;

X4 is selected from Gln and Lys;

X5 is selected from Thr and Ala;

X6 is selected from Asn and Thr; and

X7, if present, is Asn; and

v) Formula IV is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu, Asn, Arg, Ala, Ser, and Lys;

X2 is selected from Gly, Glu, Ala, Val, Thr, and Asp;

X3 is selected from Glu, Thr, Gly, Asp, or Pro;

X4 is selected from Thr, Ile, Gly, Lys, Asp, and Gln;

X5 is selected from Thr, Ser, Val, and Ala;

X6 is selected from Arg, Val, Lys, Pro, Thr, and Asn; and

X7 is selected from Pro, Gly, Phe, Asn, and Arg; and

b) a heterologous nucleic acid comprising a nucleotide sequence encoding a gene product.

[0006b] In another aspect, there is provided a pharmaceutical composition comprising:

a) a recombinant adeno-associated virus virion described herein; and

b) a pharmaceutically acceptable excipient.

[0006c] In another aspect, there is provided use of a recombinant adeno-associated virus (rAAV) virion described herein in the manufacture of a medicament for delivering a gene product to a retinal cell in an individual.

[0006d] In another aspect, there is provided use of a recombinant adeno-associated virus (rAAV) virion described herein in the manufacture of a medicament for treating a retinal disease in an individual.

[0006e] In another aspect, there is provided an isolated nucleic acid comprising a nucleotide sequence that encodes a variant adeno-associated virus (AAV) capsid protein, wherein the variant AAV capsid protein comprises a peptide insertion relative to a corresponding parental AAV capsid protein,

wherein the insertion site is located between two adjacent amino acids at a position between amino acids 570 and 611 of VP1 of AAV2 or the corresponding position in the capsid protein of another AAV serotype,

wherein the peptide insertion is a peptide of Formula I, Formula IIa, Formula IIb, Formula III, or Formula IV, wherein:

i) Formula I is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu, Asn, and Lys;

X2 is selected from Gly, Glu, Ala, and Asp;

X3 is selected from Glu, Thr, Gly, and Pro;

X4 is selected from Thr, Ile, Gln, and Lys;

X5 is selected from Thr and Ala;

X6 is selected from Arg, Asn, and Thr; and

X7, if present, is selected from Pro and Asn;

ii) Formula IIa is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

each of X1 – X4 is any amino acid;

X5 is Thr;

X6 is Arg; and

X7 is Pro;

iii) Formula IIb is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu and Asn;

X2, if present, is selected from Gly and Glu;

X3 is selected from Glu and Thr;

X4 is selected from Thr and Ile;

X5 is Thr;

X6 is Arg; and

X7 is Pro;

iv) Formula III is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is Lys;

X2 is selected from Ala and Asp;

X3 is selected from Gly and Pro;

X4 is selected from Gln and Lys;

X5 is selected from Thr and Ala;

X6 is selected from Asn and Thr; and

X7, if present, is Asn; and

v) Formula IV is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu, Asn, Arg, Ala, Ser, and Lys;

X2 is selected from Gly, Glu, Ala, Val, Thr, and Asp;

X3 is selected from Glu, Thr, Gly, Asp, or Pro;

X4 is selected from Thr, Ile, Gly, Lys, Asp, and Gln;

X5 is selected from Thr, Ser, Val, and Ala;

X6 is selected from Arg, Val, Lys, Pro, Thr, and Asn; and

X7 is selected from Pro, Gly, Phe, Asn, and Arg,

and wherein the AAV variant capsid protein, when present in an AAV virion, provides for increased infectivity of the AAV virion of a retinal cell.

[0006f] In another aspect, there is provided an isolated, genetically modified host cell comprising the nucleic acid described herein.

[0006g] In another aspect, there is provided a variant adeno-associated virus (AAV) capsid protein, wherein the variant AAV capsid protein comprises a peptide insertion relative to a corresponding parental AAV capsid protein, wherein the insertion site is located between two adjacent amino acids at a position between amino acids 570 and 611 of VP1 of AAV2 or the corresponding position in the capsid protein of another AAV serotype, wherein the insertion is a peptide of Formula I, Formula IIa, Formula IIb, Formula III, or Formula IV, and wherein:

i) Formula I is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu, Asn, and Lys;

X2 is selected from Gly, Glu, Ala, and Asp;

X3 is selected from Glu, Thr, Gly, and Pro;

X4 is selected from Thr, Ile, Gln, and Lys;

X5 is selected from Thr and Ala;

X6 is selected from Arg, Asn, and Thr; and

X7, if present, is selected from Pro and Asn;

ii) Formula IIa is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

each of X1 – X4 is any amino acid;

X5 is Thr;

X6 is Arg; and

X7 is Pro;

iii) Formula IIb is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu and Asn;

X2, if present, is selected from Gly and Glu;

X3 is selected from Glu and Thr;

X4 is selected from Thr and Ile;

X5 is Thr;

X6 is Arg; and

X7 is Pro;

iv) Formula III is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is Lys;

X2 is selected from Ala and Asp;

X3 is selected from Gly and Pro;

X4 is selected from Gln and Lys;

X5 is selected from Thr and Ala;

X6 is selected from Asn and Thr; and

X7, if present, is Asn; and

v) Formula IV is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu, Asn, Arg, Ala, Ser, and Lys;

X2 is selected from Gly, Glu, Ala, Val, Thr, and Asp;

X3 is selected from Glu, Thr, Gly, Asp, or Pro;

X4 is selected from Thr, Ile, Gly, Lys, Asp, and Gln;

X5 is selected from Thr, Ser, Val, and Ala;

X6 is selected from Arg, Val, Lys, Pro, Thr, and Asn; and

X7 is selected from Pro, Gly, Phe, Asn, and Arg.

[0006h] In another aspect, there is provided a nucleic acid comprising a nucleotide sequence encoding the variant AAV capsid protein described herein.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007] Figure 1 provides a representative three-dimensional model of AAV2 containing a random heptamer following amino acid 587.

[0008] Figure 2 depicts greater levels of intravitreal transduction by AAV2 7M8 variant (right), relative to AAV2 (left).

[0009] Figure 3 provides representative fluorescence images of retinal cryoslices showing green fluorescent protein (GFP) expression resulting from 7M8 carrying the GFP gene under

the control of the ubiquitous CAG promoter (left) or a photoreceptor-specific Rho promoter (right).

[0010] Figure 4 depicts GFP^+ photoreceptor cells per million retinal cells as counted by flow cytometry, following transduction by 7M8 or by 7M8 bearing 4 tyrosine mutations (7m8.4YF).

[0011] Figure 5 provides an amino acid sequence of AAV2 VP1 (SEQ ID NO:1).

[0012] Figure 6 provides amino acid sequences corresponding to amino acids 570-610 of AAV2 (Figure 5) of AAV capsid protein VP1 of various AAV serotypes.

[0013] Figures 7A-I depict structural improvements in the *Rs1h*-/- mouse retina after gene transfer.

[0014] Figures 8A-D depict functional rescue of the electroretinogram A and B waves following RS1 gene delivery.

[0015] Figures 9A-E depict sustained improvements in retinal thickness measured at 10 months post 7m8-rho-RS1 treatment.

[0016] Figure 10 provides an amino acid sequence of retinoschisin.

[0017] Figure 11 provides an amino acid sequence of brain derived neurotrophic factor.

[0018] Figure 12 provides an amino acid sequence of RPE65.

[0019] Figures 13A-C provide the nucleotide sequence of the 7m8-rho-RS1 construct.

[0020] Figure 14 provides an amino acid sequence of peripherin-2.

[0021] Figure 15 provides an amino acid sequence of peripherin.

[0022] Figure 16 provides an amino acid sequence of retinitis pigmentosa GTPase regulator-interacting protein-1.

[0023] Figures 17A-C provide an alignment of amino acid sequences of AAV capsid protein loop IV (GH loop) regions. Insertion sites are shown in bold and underlining.

[0024] Figures 18A-C provide an alignment of amino acid sequences of AAV capsid protein GH loop regions, with heterologous peptide insertions.

[0025] Figure 19 provides a fluorescence fundus image showing GFP expression in central primate retina 9 weeks after administration of 7m8 carrying GFP under the control of a connexin36 promoter.

DEFINITIONS

[0026] The term "retinal cell" can refer herein to any of the cell types that comprise the retina, such as retinal ganglion cells, amacrine cells, horizontal cells, bipolar cells, and photoreceptor cells including rods and cones, Müller glial cells, and retinal pigmented epithelium.

[0027] "AAV" is an abbreviation for adeno-associated virus, and may be used to refer to the virus itself or derivatives thereof. The term covers all subtypes and both naturally occurring and recombinant forms, except where required otherwise. The abbreviation "rAAV" refers to recombinant adeno-associated virus, also referred to as a recombinant AAV vector (or "rAAV vector"). The term "AAV" includes AAV type 1 (AAV-1), AAV type 2 (AAV-2), AAV type 3 (AAV-3), AAV type 4 (AAV-4), AAV type 5 (AAV-5), AAV type 6 (AAV-6), AAV type 7 (AAV-7), AAV type 8 (AAV-8), avian AAV, bovine AAV, canine AAV, equine AAV, primate AAV, non-primate AAV, and ovine AAV. "Primate AAV" refers to AAV that infect primates, "non-primate AAV" refers to AAV that infect non-primate mammals, "bovine AAV" refers to AAV that infect bovine mammals, etc.

[0028] The genomic sequences of various serotypes of AAV, as well as the sequences of the native terminal repeats (TRs), Rep proteins, and capsid subunits are known in the art. Such sequences may be found in the literature or in public databases such as GenBank. See, e.g., GenBank Accession Numbers NC_002077 (AAV-1), AF063497 (AAV-1), NC_001401 (AAV-2), AF043303 (AAV-2), NC_001729 (AAV-3), NC_001829 (AAV-4), U89790 (AAV-4), NC_006152 (AAV-5), AF513851 (AAV-7), AF513852 (AAV-8), and NC_006261 (AAV-8); the disclosures of which are incorporated by reference herein for teaching AAV nucleic acid and amino acid sequences. See also, e.g., Srivistava et al. (1983) *J. Virology* 45:555; Chiorini et al. (1998) *J. Virology* 71:6823; Chiorini et al. (1999) *J. Virology* 73:1309; Bantel-Schaal et al. (1999) *J. Virology* 73:939; Xiao et al. (1999) *J. Virology* 73:3994; Muramatsu et al. (1996) *Virology* 221:208; Shade et al.,(1986) *J. Virol.* 58:921; Gao et al. (2002) *Proc. Nat. Acad. Sci. USA* 99:11854; Moris et al. (2004) *Virology* 33:375-383; international patent publications WO 00/28061, WO 99/61601, WO 98/11244; and U.S. Pat. No. 6,156,303.

[0029] An "rAAV vector" as used herein refers to an AAV vector comprising a polynucleotide sequence not of AAV origin (i.e., a polynucleotide heterologous to AAV), typically a sequence of interest for the genetic transformation of a cell. In general, the heterologous polynucleotide is flanked by at least one, and generally by two, AAV inverted terminal repeat sequences (ITRs). The term rAAV vector encompasses both rAAV vector particles and rAAV vector plasmids. An rAAV vector may either be single-stranded (ssAAV) or self-complementary (scAAV).

[0030] An "AAV virus" or "AAV viral particle" or "rAAV vector particle" refers to a viral particle composed of at least one AAV capsid protein (typically by all of the capsid proteins of a wild-type AAV) and an encapsidated polynucleotide rAAV vector. If the particle comprises a heterologous polynucleotide (i.e. a polynucleotide other than a wild-type AAV genome such as a transgene to be delivered to a mammalian cell), it is typically referred to as an "rAAV vector particle" or simply an "rAAV vector". Thus, production of rAAV particle necessarily includes production of rAAV vector, as such a vector is contained within an rAAV particle.

[0031] "Packaging" refers to a series of intracellular events that result in the assembly and encapsidation of an AAV particle.

[0032] AAV "rep" and "cap" genes refer to polynucleotide sequences encoding replication and encapsidation proteins of adeno-associated virus. AAV rep and cap are referred to herein as AAV "packaging genes."

[0033] A "helper virus" for AAV refers to a virus that allows AAV (e.g. wild-type AAV) to be replicated and packaged by a mammalian cell. A variety of such helper viruses for AAV are known in the art, including adenoviruses, herpesviruses and poxviruses such as vaccinia. The adenoviruses encompass a number of different subgroups, although Adenovirus type 5 of subgroup C is most commonly used. Numerous adenoviruses of human, non-human mammalian and avian origin are known and available from depositories such as the ATCC. Viruses of the herpes family include, for example, herpes simplex viruses (HSV) and Epstein-Barr viruses (EBV), as well as cytomegaloviruses (CMV) and pseudorabies viruses (PRV); which are also available from depositories such as ATCC.

[0034] "Helper virus function(s)" refers to function(s) encoded in a helper virus genome which allow AAV replication and packaging (in conjunction with other requirements for replication and packaging described herein). As described herein, "helper virus function" may be provided in a number of ways, including by providing helper virus or providing, for example, polynucleotide sequences encoding the requisite function(s) to a producer cell in trans. For example, a plasmid or other expression vector comprising nucleotide sequences encoding one or more adenoviral proteins is transfected into a producer cell along with an rAAV vector.

[0035] An "infectious" virus or viral particle is one that comprises a competently assembled viral capsid and is capable of delivering a polynucleotide component into a cell for which the viral species is tropic. The term does not necessarily imply any replication capacity of the virus. Assays for counting infectious viral particles are described elsewhere in this disclosure and in the art. Viral infectivity can be expressed as the ratio of infectious viral particles to total viral particles. Methods of determining the ratio of infectious viral particle to total viral particle are known in the art. See, e.g., Grainger et al. (2005) *Mol. Ther.* 11:S337 (describing a TCID50 infectious titer assay); and Zolotukhin et al. (1999) *Gene Ther.* 6:973. See also the Examples.

[0036] A "replication-competent" virus (e.g. a replication-competent AAV) refers to a phenotypically wild-type virus that is infectious, and is also capable of being replicated

in an infected cell (i.e. in the presence of a helper virus or helper virus functions). In the case of AAV, replication competence generally requires the presence of functional AAV packaging genes. In general, rAAV vectors as described herein are replication-incompetent in mammalian cells (especially in human cells) by virtue of the lack of one or more AAV packaging genes. Typically, such rAAV vectors lack any AAV packaging gene sequences in order to minimize the possibility that replication competent AAV are generated by recombination between AAV packaging genes and an incoming rAAV vector. In many embodiments, rAAV vector preparations as described herein are those which contain few if any replication competent AAV (rcAAV, also referred to as RCA) (e.g., less than about 1 rcAAV per 10^2 rAAV particles, less than about 1 rcAAV per 10^4 rAAV particles, less than about 1 rcAAV per 10^8 rAAV particles, less than about 1 rcAAV per 10^{12} rAAV particles, or no rcAAV).

[0037] The term "polynucleotide" refers to a polymeric form of nucleotides of any length, including deoxyribonucleotides or ribonucleotides, or analogs thereof. A polynucleotide may comprise modified nucleotides, such as methylated nucleotides and nucleotide analogs, and may be interrupted by non-nucleotide components. If present, modifications to the nucleotide structure may be imparted before or after assembly of the polymer. The term polynucleotide, as used herein, refers interchangeably to double- and single-stranded molecules. Unless otherwise specified or required, any embodiment of the invention described herein that is a polynucleotide encompasses both the double-stranded form and each of two complementary single-stranded forms known or predicted to make up the double-stranded form.

[0038] Nucleic acid hybridization reactions can be performed under conditions of different "stringency". Conditions that increase stringency of a hybridization reaction of widely known and published in the art. See, e.g., Sambrook et al. *Molecular Cloning, A Laboratory Manual*, 2nd Ed., Cold Spring Harbor Laboratory Press, Cold Spring Harbor, N.Y., 1989, herein incorporated by reference. For example, see page 7.52 of Sambrook et al. Examples of relevant conditions include (in order of increasing stringency): incubation temperatures of 25°C, 37°C, 50°C and 68°C; buffer concentrations of 10 x SSC, 6 x SSC, 1 x SSC, 0.1 x SSC (where 1 x SSC is 0.15 M NaCl and 15 mM citrate buffer) and their equivalents using other buffer systems; formamide concentrations of 0%, 25%, 50%, and 75%; incubation times from 5 minutes

to 24 hours; 1, 2, or more washing steps; wash incubation times of 1, 2, or 15 minutes; and wash solutions of 6 x SSC, 1 x SSC, 0.1 x SSC, or deionized water. An example of stringent hybridization conditions is hybridization at 50°C or higher and 0.1×SSC (15 mM sodium chloride/1.5 mM sodium citrate). Another example of stringent hybridization conditions is overnight incubation at 42°C in a solution: 50% formamide, 1 × SSC (150 mM NaCl, 15 mM sodium citrate), 50 mM sodium phosphate (pH 7.6), 5 × Denhardt's solution, 10% dextran sulfate, and 20 μg/ml denatured, sheared salmon sperm DNA, followed by washing the filters in 0.1 × SSC at about 65°C. As another example, stringent hybridization conditions comprise: prehybridization for 8 hours to overnight at 65° C in a solution comprising 6X single strength citrate (SSC) (1X SSC is 0.15 M NaCl, 0.015 M Na citrate; pH 7.0), 5X Denhardt's solution, 0.05% sodium pyrophosphate and 100 μg/ml herring sperm DNA; hybridization for 18-20 hours at 65° C in a solution containing 6X SSC, 1X Denhardt's solution, 100 μg/ml yeast tRNA and 0.05% sodium pyrophosphate; and washing of filters at 65° C for 1 h in a solution containing 0.2X SSC and 0.1% SDS (sodium dodecyl sulfate).

[0039] Stringent hybridization conditions are hybridization conditions that are at least as stringent as the above representative conditions. Other stringent hybridization conditions are known in the art and may also be employed to identify nucleic acids of this particular embodiment of the invention.

[0040] "T_m" is the temperature in degrees Celsius at which 50% of a polynucleotide duplex made of complementary strands hydrogen bonded in anti-parallel direction by Watson-Crick base pairing dissociates into single strands under conditions of the experiment. T_m may be predicted according to a standard formula, such as:

[0041] $T_m = 81.5 + 16.6 \log[X^+] + 0.41$ (%G/C) - 0.61 (%F) - 600/L

[0042] where $[X^+]$ is the cation concentration (usually sodium ion, Na^+) in mol/L; (%G/C) is the number of G and C residues as a percentage of total residues in the duplex; (%F) is the percent formamide in solution (wt/vol); and L is the number of nucleotides in each strand of the duplex.

[0043] A polynucleotide or polypeptide has a certain percent "sequence identity" to another polynucleotide or polypeptide, meaning that, when aligned, that percentage of bases or amino acids are the same when comparing the two sequences. Sequence similarity can be determined in a number of different manners. To determine sequence identity,

sequences can be aligned using the methods and computer programs, including BLAST, available over the world wide web at ncbi.nlm.nih.gov/BLAST/. Another alignment algorithm is FASTA, available in the Genetics Computing Group (GCG) package, from Madison, Wisconsin, USA, a wholly owned subsidiary of Oxford Molecular Group, Inc. Other techniques for alignment are described in Methods in Enzymology, vol. 266: Computer Methods for Macromolecular Sequence Analysis (1996), ed. Doolittle, Academic Press, Inc., a division of Harcourt Brace & Co., San Diego, California, USA. Of particular interest are alignment programs that permit gaps in the sequence. The Smith-Waterman is one type of algorithm that permits gaps in sequence alignments. See *Meth. Mol. Biol.* 70: 173-187 (1997). Also, the GAP program using the Needleman and Wunsch alignment method can be utilized to align sequences. See *J. Mol. Biol.* 48: 443-453 (1970)

[0044] Of interest is the BestFit program using the local homology algorithm of Smith and Waterman (Advances in Applied Mathematics 2: 482-489 (1981) to determine sequence identity. The gap generation penalty will generally range from 1 to 5, usually 2 to 4 and in many embodiments will be 3. The gap extension penalty will generally range from about 0.01 to 0.20 and in many instances will be 0.10. The program has default parameters determined by the sequences inputted to be compared. Preferably, the sequence identity is determined using the default parameters determined by the program. This program is available also from Genetics Computing Group (GCG) package, from Madison, Wisconsin, USA.

[0045] Another program of interest is the FastDB algorithm. FastDB is described in Current Methods in Sequence Comparison and Analysis, Macromolecule Sequencing and Synthesis, Selected Methods and Applications; pp. 127-149, 1988, Alan R. Liss, Inc. Percent sequence identity is calculated by FastDB based upon the following parameters:

[0046] Mismatch Penalty: 1.00;

[0047] Gap Penalty: 1.00;

[0048] Gap Size Penalty: 0.33; and

[0049] Joining Penalty: 30.0.

[0050] A "gene" refers to a polynucleotide containing at least one open reading frame that is capable of encoding a particular protein after being transcribed and translated.

[0051] A "gene product" is a molecule resulting from expression of a particular gene. Gene products include, e.g., a polypeptide, an aptamer, an interfering RNA, an mRNA, and the like.

[0052] A "small interfering" or "short interfering RNA" or siRNA is a RNA duplex of nucleotides that is targeted to a gene interest (a "target gene"). An "RNA duplex" refers to the structure formed by the complementary pairing between two regions of a RNA molecule. siRNA is "targeted" to a gene in that the nucleotide sequence of the duplex portion of the siRNA is complementary to a nucleotide sequence of the targeted gene. In some embodiments, the length of the duplex of siRNAs is less than 30 nucleotides. In some embodiments, the duplex can be 29, 28, 27, 26, 25, 24, 23, 22, 21, 20, 19, 18, 17, 16, 15, 14, 13, 12, 11 or 10 nucleotides in length. In some embodiments, the length of the duplex is 19-25 nucleotides in length. The RNA duplex portion of the siRNA can be part of a hairpin structure. In addition to the duplex portion, the hairpin structure may contain a loop portion positioned between the two sequences that form the duplex. The loop can vary in length. In some embodiments the loop is 5, 6, 7, 8, 9, 10, 11, 12 or 13 nucleotides in length. The hairpin structure can also contain 3' or 5' overhang portions. In some embodiments, the overhang is a 3' or a 5' overhang 0, 1, 2, 3, 4 or 5 nucleotides in length.

[0053] A "short hairpin RNA," or shRNA, is a polynucleotide construct that can be made to express an interfering RNA such as siRNA.

[0054] "Recombinant," as applied to a polynucleotide means that the polynucleotide is the product of various combinations of cloning, restriction or ligation steps, and other procedures that result in a construct that is distinct from a polynucleotide found in nature. A recombinant virus is a viral particle comprising a recombinant polynucleotide. The terms respectively include replicates of the original polynucleotide construct and progeny of the original virus construct.

[0055] A "control element" or "control sequence" is a nucleotide sequence involved in an interaction of molecules that contributes to the functional regulation of a polynucleotide, including replication, duplication, transcription, splicing, translation, or degradation of the polynucleotide. The regulation may affect the frequency, speed, or specificity of the process, and may be enhancing or inhibitory in nature. Control elements known in the art include, for example, transcriptional regulatory sequences such as promoters and

enhancers. A promoter is a DNA region capable under certain conditions of binding RNA polymerase and initiating transcription of a coding region usually located downstream (in the 3' direction) from the promoter.

[0056] "Operatively linked" or "operably linked" refers to a juxtaposition of genetic elements, wherein the elements are in a relationship permitting them to operate in the expected manner. For instance, a promoter is operatively linked to a coding region if the promoter helps initiate transcription of the coding sequence. There may be intervening residues between the promoter and coding region so long as this functional relationship is maintained.

[0057] An "expression vector" is a vector comprising a region which encodes a polypeptide of interest, and is used for effecting the expression of the protein in an intended target cell. An expression vector also comprises control elements operatively linked to the encoding region to facilitate expression of the protein in the target. The combination of control elements and a gene or genes to which they are operably linked for expression is sometimes referred to as an "expression cassette," a large number of which are known and available in the art or can be readily constructed from components that are available in the art.

[0058] "Heterologous" means derived from a genotypically distinct entity from that of the rest of the entity to which it is being compared. For example, a polynucleotide introduced by genetic engineering techniques into a plasmid or vector derived from a different species is a heterologous polynucleotide. A promoter removed from its native coding sequence and operatively linked to a coding sequence with which it is not naturally found linked is a heterologous promoter. Thus, for example, an rAAV that includes a heterologous nucleic acid encoding a heterologous gene product is an rAAV that includes a nucleic acid not normally included in a naturally-occurring, wild-type AAV, and the encoded heterologous gene product is a gene product not normally encoded by a naturally-occurring, wild-type AAV.

[0059] The terms "genetic alteration" and "genetic modification" (and grammatical variants thereof), are used interchangeably herein to refer to a process wherein a genetic element (e.g., a polynucleotide) is introduced into a cell other than by mitosis or meiosis. The element may be heterologous to the cell, or it may be an additional copy or improved version of an element already present in the cell. Genetic alteration may be effected, for

example, by transfecting a cell with a recombinant plasmid or other polynucleotide through any process known in the art, such as electroporation, calcium phosphate precipitation, or contacting with a polynucleotide-liposome complex. Genetic alteration may also be effected, for example, by transduction or infection with a DNA or RNA virus or viral vector. Generally, the genetic element is introduced into a chromosome or mini-chromosome in the cell; but any alteration that changes the phenotype and/or genotype of the cell and its progeny is included in this term.

[0060] A cell is said to be "stably" altered, transduced, genetically modified, or transformed with a genetic sequence if the sequence is available to perform its function during extended culture of the cell in vitro. Generally, such a cell is "heritably" altered (genetically modified) in that a genetic alteration is introduced which is also inheritable by progeny of the altered cell.

[0061] The terms "polypeptide," "peptide," and "protein" are used interchangeably herein to refer to polymers of amino acids of any length. The terms also encompass an amino acid polymer that has been modified; for example, disulfide bond formation, glycosylation, lipidation, phosphorylation, or conjugation with a labeling component. Polypeptides such as anti-angiogenic polypeptides, neuroprotective polypeptides, and the like, when discussed in the context of delivering a gene product to a mammalian subject, and compositions therefor, refer to the respective intact polypeptide, or any fragment or genetically engineered derivative thereof, which retains the desired biochemical function of the intact protein. Similarly, references to nucleic acids encoding anti-angiogenic polypeptides, nucleic acids encoding neuroprotective polypeptides, and other such nucleic acids for use in delivery of a gene product to a mammalian subject (which may be referred to as "transgenes" to be delivered to a recipient cell), include polynucleotides encoding the intact polypeptide or any fragment or genetically engineered derivative possessing the desired biochemical function.

[0062] An "isolated" plasmid, nucleic acid, vector, virus, virion, host cell, or other substance refers to a preparation of the substance devoid of at least some of the other components that may also be present where the substance or a similar substance naturally occurs or is initially prepared from. Thus, for example, an isolated substance may be prepared by using a purification technique to enrich it from a source mixture. Enrichment can be measured on an absolute basis, such as weight per volume of solution, or it can be

measured in relation to a second, potentially interfering substance present in the source mixture. Increasing enrichments of the embodiments of this disclosure are increasingly more isolated. An isolated plasmid, nucleic acid, vector, virus, host cell, or other substance is in some embodiments purified, e.g., from about 80% to about 90% pure, at least about 90% pure, at least about 95% pure, at least about 98% pure, or at least about 99%, or more, pure.

[0063] As used herein, the terms "treatment," "treating," and the like, refer to obtaining a desired pharmacologic and/or physiologic effect. The effect may be prophylactic in terms of completely or partially preventing a disease or symptom thereof and/or may be therapeutic in terms of a partial or complete cure for a disease and/or adverse effect attributable to the disease. "Treatment," as used herein, covers any treatment of a disease in a mammal, particularly in a human, and includes: (a) preventing the disease from occurring in a subject which may be predisposed to the disease or at risk of acquiring the disease but has not yet been diagnosed as having it; (b) inhibiting the disease, i.e., arresting its development; and (c) relieving the disease, i.e., causing regression of the disease.

[0064] The terms "individual," "host," "subject," and "patient" are used interchangeably herein, and refer to a mammal, including, but not limited to, human and non-human primates, including simians and humans; mammalian sport animals (e.g., horses); mammalian farm animals (e.g., sheep, goats, etc.); mammalian pets (dogs, cats, etc.); and rodents (e.g., mice, rats, etc.).

[0065] Before the present invention is further described, it is to be understood that this invention is not limited to particular embodiments described, as such may, of course, vary. It is also to be understood that the terminology used herein is for the purpose of describing particular embodiments only, and is not intended to be limiting, since the scope of the present invention will be limited only by the appended claims.

[0066] Where a range of values is provided, it is understood that each intervening value, to the tenth of the unit of the lower limit unless the context clearly dictates otherwise, between the upper and lower limit of that range and any other stated or intervening value in that stated range, is encompassed within the invention. The upper and lower limits of these smaller ranges may independently be included in the smaller ranges, and are also

encompassed within the invention, subject to any specifically excluded limit in the stated range. Where the stated range includes one or both of the limits, ranges excluding either or both of those included limits are also included in the invention.

[0067] Unless defined otherwise, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. Although any methods and materials similar or equivalent to those described herein can also be used in the practice or testing of the present invention, the preferred methods and materials are now described. All publications mentioned herein are incorporated herein by reference to disclose and describe the methods and/or materials in connection with which the publications are cited.

[0068] It must be noted that as used herein and in the appended claims, the singular forms "a," "an," and "the" include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to "a recombinant AAV virion" includes a plurality of such virions and reference to "the photoreceptor cell" includes reference to one or more photoreceptor cells and equivalents thereof known to those skilled in the art, and so forth. It is further noted that the claims may be drafted to exclude any optional element. As such, this statement is intended to serve as antecedent basis for use of such exclusive terminology as "solely," "only" and the like in connection with the recitation of claim elements, or use of a "negative" limitation.

[0069] It is appreciated that certain features of the invention, which are, for clarity, described in the context of separate embodiments, may also be provided in combination in a single embodiment. Conversely, various features of the invention, which are, for brevity, described in the context of a single embodiment, may also be provided separately or in any suitable sub-combination. All combinations of the embodiments pertaining to the invention are specifically embraced by the present invention and are disclosed herein just as if each and every combination was individually and explicitly disclosed. In addition, all sub-combinations of the various embodiments and elements thereof are also specifically embraced by the present invention and are disclosed herein just as if each and every such sub-combination was individually and explicitly disclosed herein.

[0070] The publications discussed herein are provided solely for their disclosure prior to the filing date of the present application. Nothing herein is to be construed as an admission that the present invention is not entitled to antedate such publication by virtue of prior

invention. Further, the dates of publication provided may be different from the actual publication dates which may need to be independently confirmed.

DETAILED DESCRIPTION

[0071] The present disclosure provides adeno-associated virus (AAV) virions with altered capsid protein, where the AAV virions exhibit greater infectivity of a retinal cell, when administered via intravitreal injection, compared to wild-type AAV when administered via intravitreal injection. The present disclosure further provides methods of delivering a gene product to a retinal cell in an individual, and methods of treating ocular disease.

[0072] The retinal cell can be a photoreceptor (e.g., rods; cones), a retinal ganglion cell (RGC), a Müller cell (a Müller glial cell), a bipolar cell, an amacrine cell, a horizontal cell, or a retinal pigmented epithelium (RPE) cell.

VARIANT AAV CAPSID POLYPEPTIDES

[0073] The present disclosure provides a variant AAV capsid protein, where the variant AAV capsid protein comprises an insertion of from about 5 amino acids to about 11 amino acids in an insertion site in the capsid protein GH loop or loop IV, relative to a corresponding parental AAV capsid protein, and where the variant capsid protein, when present in an AAV virion, confers increased infectivity of a retinal cell compared to the infectivity of the retinal cell by an AAV virion comprising the corresponding parental AAV capsid protein. In some cases, the retinal cell is a photoreceptor cell (e.g., rods; cones). In other cases, the retinal cell is an RGC. In other cases, the retinal cell is an RPE cell. In other cases, the retinal cell is a Müller cell. Other retinal cells include amacrine cells, bipolar cells, and horizontal cells. An "insertion of from about 5 amino acids to about 11 amino acids" is also referred to herein as a "peptide insertion" (e.g., a heterologous peptide insertion). A "corresponding parental AAV capsid protein" refers to an AAV capsid protein of the same AAV serotype, without the peptide insertion.

[0074] The insertion site is in the GH loop, or loop IV, of the AAV capsid protein, e.g., in a solvent-accessible portion of the GH loop, or loop IV, of the AAV capsid protein. For the GH loop/loop IV of AAV capsid, see, e.g., van Vliet et al. (2006) *Mol. Ther.* 14:809; Padron et al. (2005) *J. Virol.* 79:5047; and Shen et al. (2007) *Mol. Ther.* 15:1955. For example, the insertion site can be within amino acids 411-650 of an AAV capsid protein, as depicted in Figures 17A and 17B. For example, the insertion site can be within amino

acids 570-611 of AAV2, within amino acids 571-612 of AAV1, within amino acids 560-601 of AAV5, within amino acids 571 to 612 of AAV6, within amino acids 572 to 613 of AAV7, within amino acids 573 to 614 of AAV8, within amino acids 571 to 612 of AAV9, or within amino acids 573 to 614 of AAV10, as depicted in Figure 6.

[0075] In some cases, from about 5 amino acids to about 11 amino acids are inserted in an insertion site in the GH loop or loop IV of the capsid protein relative to a corresponding parental AAV capsid protein. For example, the insertion site can be between amino acids 587 and 588 of AAV2, or the corresponding positions of the capsid subunit of another AAV serotype. It should be noted that the insertion site 587/588 is based on an AAV2 capsid protein. From about 5 amino acids to about 11 amino acids can be inserted in a corresponding site in an AAV serotype other than AAV2 (e.g., AAV8, AAV9, etc.). Those skilled in the art would know, based on a comparison of the amino acid sequences of capsid proteins of various AAV serotypes, where an insertion site "corresponding to amino acids 587-588 of AAV2" would be in a capsid protein of any given AAV serotype. Sequences corresponding to amino acids 570-611 of capsid protein VP1 of AAV2 (see Figure 5) in various AAV serotypes are shown in Figure 6. See, e.g., GenBank Accession No. NP_049542 for AAV1; GenBank Accession No. AAD13756 for AAV5; GenBank Accession No. AAB95459 for AAV6; GenBank Accession No. YP_077178 for AAV7; GenBank Accession No. YP_077180 for AAV8; GenBank Accession No. AAS99264 for AAV9 and GenBank Accession No. AAT46337 for AAV10.

[0076] In some embodiments, the insertion site is a single insertion site between two adjacent amino acids located between amino acids 570-614 of VP1 of any AAV serotype, e.g., the insertion site is between two adjacent amino acids located in amino acids 570-610, amino acids 580-600, amino acids 570-575, amino acids 575-580, amino acids 580-585, amino acids 585-590, amino acids 590-600, or amino acids 600-614, of VP1 of any AAV serotype or variant. For example, the insertion site can be between amino acids 580 and 581, amino acids 581 and 582, amino acids 583 and 584, amino acids 584 and 585, amino acids 585 and 586, amino acids 586 and 587, amino acids 587 and 588, amino acids 588 and 589, or amino acids 589 and 590. The insertion site can be between amino acids 575 and 576, amino acids 576 and 577, amino acids 577 and 578, amino acids 578 and 579, or amino acids 579 and 580. The insertion site can be between amino

acids 590 and 591, amino acids 591 and 592, amino acids 592 and 593, amino acids 593 and 594, amino acids 594 and 595, amino acids 595 and 596, amino acids 596 and 597, amino acids 597 and 598, amino acids 598 and 599, or amino acids 599 and 600.

[0077] For example, the insertion site can be between amino acids 587 and 588 of AAV2, between amino acids 590 and 591 of AAV1, between amino acids 575 and 576 of AAV5, between amino acids 590 and 591 of AAV6, between amino acids 589 and 590 of AAV7, between amino acids 590 and 591 of AAV8, between amino acids 588 and 589 of AAV9, or between amino acids 588 and 589 of AAV10.

[0078] As another example, the insertion site can be between amino acids 450 and 460 of an AAV capsid protein, as shown in Figure 17A. For example, the insertion site can be at (e.g., immediately N-terminal to) amino acid 453 of AAV2, at amino acid 454 of AAV1, at amino acid 454 of AAV6, at amino acid 456 of AAV7, at amino acid 456 of AAV8, at amino acid 454 of AAV9, or at amino acid 456 of AAV10, as shown in Figure 17A.

[0079] In some embodiments, a subject capsid protein includes a GH loop comprising an amino acid sequence having at least about 85%, at least about 90%, at least about 95%, at least about 98%, at least about 99%, or 100%, amino acid sequence identity to an amino acid sequence set forth in Figure 18A-C.

Insertion peptides

[0080] As noted above, a peptide of from about 5 amino acids to about 11 amino acids in length is inserted into the GH loop of an AAV capsid. The insertion peptide has a length of 5 amino acids, 6 amino acids, 7 amino acids, 8 amino acids, 9 amino acids, 10 amino acids, or 11 amino acids.

[0081] The insertion peptide can comprise an amino acid sequence of any one of the formulas set forth below.

[0082] For example, an insertion peptide can be a peptide of from 5 to 11 amino acids in length, where the insertion peptide is of **Formula I:**

[0083] $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$

[0084] where:

each of Y_1 –Y_4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X_1, if present, is selected from Leu, Asn, and Lys;

X_2 is selected from Gly, Glu, Ala, and Asp;

X_3 is selected from Glu, Thr, Gly, and Pro;

X_4 is selected from Thr, Ile, Gln, and Lys;

X_5 is selected from Thr and Ala;

X_6 is selected from Arg, Asn, and Thr;

X_7, if present, is selected from Pro and Asn.

[0085] As another example, an insertion peptide can be a peptide of from 5 to 11 amino acids in length, where the insertion peptide is of **Formula IIa:**

[0086] $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$

[0087] where:

each of Y_1 –Y_4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

each of X_1 – X_4 is any amino acid;

X_5 is Thr;

X_6 is Arg; and

X_7 is Pro.

[0088] As another example, an insertion peptide can be a peptide of from 5 to 11 amino acids in length, where the insertion peptide is of **Formula IIb:**

[0089] $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$

[0090] where:

each of Y_1 –Y_4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X_1, if present, is selected from Leu and Asn;

X_2, if present, is selected from Gly and Glu;

X_3 is selected from Glu and Thr;

X_4 is selected from Thr and Ile;

X_5 is Thr;

X_6 is Arg; and

X_7 is Pro.

[0091] As another example, an insertion peptide can be a peptide of from 5 to 11 amino acids in length, where the insertion peptide is of **Formula III:**

[0092] $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$

[0093] where:

each of Y_1 –Y_4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X_1, if present, is Lys;

X_2 is selected from Ala and Asp;

X_3 is selected from Gly and Pro;

X_4 is selected from Gln and Lys;

X_5 is selected from Thr and Ala;

X_6 is selected from Asn and Thr;

X_7, if present, is Asn.

[0094] As another example, an insertion peptide can be a peptide of from 5 to 11 amino acids in length, where the insertion peptide is of **Formula IV:**

[0095] $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$

[0096] where:

each of Y_1 –Y_4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X_1, if present, is a positively charged amino acid or an uncharged amino acid; or is selected from Leu, Asn, Arg, Ala, Ser, and Lys;

X_2 is a negatively charged amino acid or an uncharged amino acid; or is selected from Gly, Glu, Ala, Val, Thr, and Asp;

X_3 is a negatively charged amino acid or an uncharged amino acid; or is selected from Glu, Thr, Gly, Asp, or Pro;

X_4 is selected from Thr, Ile, Gly, Lys, Asp, and Gln;

X_5 is a polar amino acid, an alcohol (an amino acid having a free hydroxyl group), or a hydrophobic amino acid; or is selected from Thr, Ser, Val, and Ala;

X_6 is a positively charged amino acid or an uncharged amino acid; or is selected from Arg, Val, Lys, Pro, Thr, and Asn; and

X_7, if present, is a positively charged amino acid or an uncharged amino acid; or is selected from Pro, Gly, Phe, Asn, and Arg.

[0097] As non-limiting examples, the insertion peptide can comprise an amino acid sequence selected from LGETTRP (SEQ ID NO:13), NETITRP (SEQ ID NO:14), KAGQANN (SEQ ID NO:15), KDPKTTN (SEQ ID NO:16), KDTDTTR (SEQ ID NO:57), RAGGSVG (SEQ ID NO:58), AVDTTKF (SEQ ID NO:59), and STGKVPN (SEQ ID NO:60).

[0098] In some cases, the insertion peptide has from 1 to 4 spacer amino acids (Y_1-Y_4) at the amino terminus and/or at the carboxyl terminus of any one of LGETTRP (SEQ ID NO:13), NETITRP (SEQ ID NO:14), KAGQANN (SEQ ID NO:15), KDPKTTN (SEQ ID NO:16), KDTDTTR (SEQ ID NO:57), RAGGSVG (SEQ ID NO:58), AVDTTKF

(SEQ ID NO:59), and STGKVPN (SEQ ID NO:60). Suitable spacer amino acids include, but are not limited to, leucine, alanine, glycine, and serine.

[0099] For example, in some cases, an insertion peptide has one of the following amino acid sequences: LALGETTRPA (SEQ ID NO:45); LANETITRPA (SEQ ID NO:46), LAKAGQANNA (SEQ ID NO:47), LAKDPKTTNA (SEQ ID NO:48), LAKDTDTTRA (SEQ ID NO:61), LARAGGSVGA (SEQ ID NO:62), LAAVDTTKFA (SEQ ID NO:63), and LASTGKVPNA (SEQ ID NO:64). As another example, in some cases, an insertion peptide has one of the following amino acid sequences: AALGETTRPA (SEQ ID NO:49); AANETITRPA (SEQ ID NO:50), AAKAGQANNA (SEQ ID NO:51), and AAKDPKTTNA (SEQ ID NO:52). As yet another example, in some cases, an insertion peptide has one of the following amino acid sequences: GLGETTRPA (SEQ ID NO:53); GNETITRPA (SEQ ID NO:54), GKAGQANNA (SEQ ID NO:55), and GKDPKTTNA (SEQ ID NO:56). As another example, in some cases, an insertion peptide comprises one of KDTDTTR (SEQ ID NO:57), RAGGSVG (SEQ ID NO:58), AVDTTKF (SEQ ID NO:59), and STGKVPN (SEQ ID NO:60), flanked on the C-terminus by AA and on the N-terminus by A; or comprises one of KDTDTTR (SEQ ID NO:57), RAGGSVG (SEQ ID NO:58), AVDTTKF (SEQ ID NO:59), and STGKVPN (SEQ ID NO:60) flanked on the C-terminus by G and on the N-terminus by A.

[00100] In some embodiments, a subject variant AAV capsid does not include any other amino acid substitutions, insertions, or deletions, other than an insertion of from about 5 amino acids to about 11 amino acids in the GH loop or loop IV relative to a corresponding parental AAV capsid protein. In other embodiments, a subject variant AAV capsid includes from 1 to about 25 amino acid insertions, deletions, or substitutions, compared to the parental AAV capsid protein, in addition to an insertion of from about 5 amino acids to about 11 amino acids in the GH loop or loop IV relative to a corresponding parental AAV capsid protein. For example, in some embodiments, a subject variant AAV capsid includes from 1 to about 5, from about 5 to about 10, from about 10 to about 15, from about 15 to about 20, or from about 20 to about 25 amino acid insertions, deletions, or substitutions, compared to the parental AAV capsid protein, in addition to an insertion of from about 5 amino acids to about 11 amino acids in the GH loop or loop IV relative to a corresponding parental AAV capsid protein.

[00101] In some embodiments, a subject variant capsid polypeptide does not include one, two, three, or four, of the following amino acid substitutions: Y273F, Y444F, Y500F, and Y730F.

[00102] In some embodiments, a subject variant capsid polypeptide comprises, in addition to an insertion peptide as described above, one, two, three, or four, of the following amino acid substitutions: Y273F, Y444F, Y500F, and Y730F.

[00103] In some embodiments, a variant AAV capsid polypeptide is a chimeric capsid, e.g., the capsid comprises a portion of an AAV capsid of a first AAV serotype and a portion of an AAV capsid of a second serotype; and comprises an insertion of from about 5 amino acids to about 11 amino acids in the GH loop or loop IV relative to a corresponding parental AAV capsid protein.

[00104] In some embodiments, a subject variant capsid protein comprises an amino acid sequence having at least about 85%, at least about 90%, at least about 95%, at least about 98%, or at least about 99%, amino acid sequence identity to the amino acid sequence provided in Figure 5; and an insertion of from about 5 amino acids to about 11 amino acids in the GH loop or loop IV relative to a corresponding parental AAV capsid protein.

[00105] In some embodiments, a subject variant capsid protein is isolated, e.g., purified. In some cases, a subject variant capsid protein is included in an AAV vector, which is also provided. As described in detail below, a subject variant capsid protein can be included in a recombinant AAV virion.

RECOMBINANT AAV VIRION

[00106] The present disclosure provides a recombinant adeno-associated virus (rAAV) virion comprising: a) a variant AAV capsid protein, where the variant AAV capsid protein comprises an insertion of from about 5 amino acids to about 11 amino acids in an insertion site in the capsid protein GH loop or loop IV, relative to a corresponding parental AAV capsid protein, and where the variant capsid protein confers increased infectivity of a retinal cell compared to the infectivity of the retinal cell by an AAV virion comprising the corresponding parental AAV capsid protein; and b) a heterologous nucleic acid comprising a nucleotide sequence encoding a gene product. In some cases, the retinal cell is a photoreceptor cell (e.g., rods and/or cones). In other cases, the retinal cell is an RGC cell. In other cases, the retinal cell is an RPE cell. In other cases, the

retinal cell is a Müller cell. In other cases, retinal cells may include amacrine cells, bipolar cells, and horizontal cells. An "insertion of from about 5 amino acids to about 11 amino acids" is also referred to herein as a "peptide insertion" (e.g., a heterologous peptide insertion). A "corresponding parental AAV capsid protein" refers to an AAV capsid protein of the same AAV serotype, without the peptide insertion.

[00107] The insertion site is in the GH loop, or loop IV, of the AAV capsid protein, e.g., in a solvent-accessible portion of the GH loop, or loop IV, of the AAV capsid protein. For the GH loop, see, e.g., van Vliet et al. (2006) *Mol. Ther.* 14:809; Padron et al. (2005) *J. Virol.* 79:5047; and Shen et al. (2007) *Mol. Ther.* 15:1955. For example, the insertion site is within amino acids 570-611 of AAV2, within amino acids 571-612 of AAV1, within amino acids 560-601 of AAV5, within amino acids 571 to 612 of AAV6, within amino acids 572 to 613 of AAV7, within amino acids 573 to 614 of AAV8, within amino acids 571 to 612 of AAV9, or within amino acids 573 to 614 of AAV10.

[00108] From about 5 amino acids to about 11 amino acids are inserted in an insertion site in the GH loop or loop IV of the capsid protein relative to a corresponding parental AAV capsid protein. For example, the insertion site can be between amino acids 587 and 588 of AAV2, or the corresponding positions of the capsid subunit of another AAV serotype. It should be noted that the insertion site 587/588 is based on an AAV2 capsid protein. From about 5 amino acids to about 11 amino acids can be inserted in a corresponding site in an AAV serotype other than AAV2 (e.g., AAV8, AAV9, etc.). Those skilled in the art would know, based on a comparison of the amino acid sequences of capsid proteins of various AAV serotypes, where an insertion site "corresponding to amino acids 587-588 of AAV2" would be in a capsid protein of any given AAV serotype. Sequences corresponding to amino acids 570-611 of capsid protein VP1 of AAV2 (see Figure 5) in various AAV serotypes are shown in Figure 6.

[00109] In some embodiments, the insertion site is a single insertion site between two adjacent amino acids located between amino acids 570-614 of VP1 of any AAV serotype, e.g., the insertion site is between two adjacent amino acids located in amino acids 570-614, amino acids 580-600, amino acids 570-575, amino acids 575-580, amino acids 580-585, amino acids 585-590, amino acids 590-600, or amino acids 600-610, of VP1 of any AAV serotype or variant. For example, the insertion site can be between amino acids 580 and 581, amino acids 581 and 582, amino acids 583 and 584, amino

acids 584 and 585, amino acids 585 and 586, amino acids 586 and 587, amino acids 587 and 588, amino acids 588 and 589, or amino acids 589 and 590. The insertion site can be between amino acids 575 and 576, amino acids 576 and 577, amino acids 577 and 578, amino acids 578 and 579, or amino acids 579 and 580. The insertion site can be between amino acids 590 and 591, amino acids 591 and 592, amino acids 592 and 593, amino acids 593 and 594, amino acids 594 and 595, amino acids 595 and 596, amino acids 596 and 597, amino acids 597 and 598, amino acids 598 and 599, or amino acids 599 and 600.

[00110] For example, the insertion site can be between amino acids 587 and 588 of AAV2, between amino acids 590 and 591 of AAV1, between amino acids 575 and 576 of AAV5, between amino acids 590 and 591 of AAV6, between amino acids 589 and 590 of AAV7, between amino acids 590 and 591 of AAV8, between amino acids 588 and 589 of AAV9, or between amino acids 589 and 590 of AAV10.

Insertion peptides

[00111] As noted above, a subject rAAV virion comprises a peptide of from about 5 amino acids to about 11 amino acids in length inserted into the GH loop of the AAV capsid. The insertion peptide has a length of 5 amino acids, 6 amino acids, 7 amino acids, 8 amino acids, 9 amino acids, 10 amino acids, or 11 amino acids.

[00112] The insertion peptide can comprise an amino acid sequence of any one of the formulas set forth below.

[00113] For example, an insertion peptide can be a peptide of from 5 to 11 amino acids in length, where the insertion peptide is of **Formula I:**

[00114] $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$

[00115] where:

each of Y_1 –Y_4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X_1, if present, is selected from Leu, Asn, and Lys;

X_2 is selected from Gly, Glu, Ala, and Asp;

X_3 is selected from Glu, Thr, Gly, and Pro;

X_4 is selected from Thr, Ile, Gln, and Lys;

X_5 is selected from Thr and Ala;

X_6 is selected from Arg, Asn, and Thr;

X_7, if present, is selected from Pro and Asn.

[00116] As another example, an insertion peptide can be a peptide of from 5 to 11 amino acids in length, where the insertion peptide is of **Formula IIa:**

[00117] $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$

[00118] where:

each of Y_1 –Y_4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

each of X_1 – X_4 is any amino acid;

X_5 is Thr;

X_6 is Arg; and

X_7 is Pro.

[00119] As another example, an insertion peptide can be a peptide of from 5 to 11 amino acids in length, where the insertion peptide is of **Formula IIb:**

[00120] $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$

[00121] where:

each of Y_1 –Y_4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X_1, if present, is selected from Leu and Asn;

X_2, if present, is selected from Gly and Glu;

X_3 is selected from Glu and Thr;

X_4 is selected from Thr and Ile;

X_5 is Thr;

X_6 is Arg; and

X_7 is Pro.

[00122] As another example, an insertion peptide can be a peptide of from 5 to 11 amino acids in length, where the insertion peptide is of **Formula III:**

[00123] $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$

[00124] where:

each of Y_1 –Y_4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X_1, if present, is Lys;

X_2 is selected from Ala and Asp;

X_3 is selected from Gly and Pro;

X_4 is selected from Gln and Lys;

X_5 is selected from Thr and Ala;

X_6 is selected from Asn and Thr;

X_7, if present, is Asn.

[00125] As another example, an insertion peptide can be a peptide of from 5 to 11 amino acids in length, where the insertion peptide is of **Formula IV:**

[00126] $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$

[00127] where:

each of Y_1 –Y_4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X_1, if present, is a positively charged amino acid or an uncharged amino acid; or is selected from Leu, Asn, Arg, Ala, Ser, and Lys;

X_2 is a negatively charged amino acid or an uncharged amino acid; or is selected from Gly, Glu, Ala, Val, Thr, and Asp;

X_3 is a negatively charged amino acid or an uncharged amino acid; or is selected from Glu, Thr, Gly, Asp, or Pro;

X_4 is selected from Thr, Ile, Gly, Lys, Asp, and Gln;

X_5 is a polar amino acid, an alcohol (an amino acid having a free hydroxyl group), or a hydrophobic amino acid; or is selected from Thr, Ser, Val, and Ala;

X_6 is a positively charged amino acid or an uncharged amino acid; or is selected from Arg, Val, Lys, Pro, Thr, and Asn; and

X_7, if present, is a positively charged amino acid or an uncharged amino acid; or is selected from Pro, Gly, Phe, Asn, and Arg.

[00128] As non-limiting examples, the insertion peptide can comprise an amino acid sequence selected from LGETTRP (SEQ ID NO:13), NETITRP (SEQ ID NO:14), KAGQANN (SEQ ID NO:15), KDPKTTN (SEQ ID NO:16), KDTDTTR (SEQ ID NO:57), RAGGSVG (SEQ ID NO:58), AVDTTKF (SEQ ID NO:59), and STGKVPN (SEQ ID NO:60).

[00129] In some cases, the insertion peptide has from 1 to 4 spacer amino acids (Y_1-Y_4) at the amino terminus and/or at the carboxyl terminus of any one of LGETTRP (SEQ ID NO:13), NETITRP (SEQ ID NO:14), KAGQANN (SEQ ID NO:15), KDPKTTN (SEQ ID NO:16), KDTDTTR (SEQ ID NO:57), RAGGSVG (SEQ ID NO:58), AVDTTKF (SEQ ID NO:59), and STGKVPN (SEQ ID NO:60). Suitable spacer amino acids include, but are not limited to, leucine, alanine, glycine, and serine.

[00130] For example, in some cases, an insertion peptide has one of the following amino acid sequences: LALGETTRPA (SEQ ID NO:45); LANETITRPA (SEQ ID NO:46),

LAKAGQANNA (SEQ ID NO:47), LAKDPKTTNA (SEQ ID NO:48), LAKDTDTTRA (SEQ ID NO:61), LARAGGSVGA (SEQ ID NO:62), LAAVDTTKFA (SEQ ID NO:63), and LASTGKVPNA (SEQ ID NO:64). As another example, in some cases, an insertion peptide has one of the following amino acid sequences: AALGETTRPA (SEQ ID NO:49); AANETITRPA (SEQ ID NO:50), AAKAGQANNA (SEQ ID NO:51), and AAKDPKTTNA (SEQ ID NO:52). As yet another example, in some cases, an insertion peptide has one of the following amino acid sequences: GLGETTRPA (SEQ ID NO:53); GNETITRPA (SEQ ID NO:54), GKAGQANNA (SEQ ID NO:55), and GKDPKTTNA (SEQ ID NO:56). As another example, in some cases, an insertion peptide comprises one of KDTDTTR (SEQ ID NO:57), RAGGSVG (SEQ ID NO:58), AVDTTKF (SEQ ID NO:59), and STGKVPN (SEQ ID NO:60), flanked on the C-terminus by AA and on the N-terminus by A; or comprises one of KDTDTTR (SEQ ID NO:57), RAGGSVG (SEQ ID NO:58), AVDTTKF (SEQ ID NO:59), and STGKVPN (SEQ ID NO:60) flanked on the C-terminus by G and on the N-terminus by A.

[00131] In some embodiments, a subject rAAV virion capsid does not include any other amino acid substitutions, insertions, or deletions, other than an insertion of from about 7 amino acids to about 10 amino acids in the GH loop or loop IV relative to a corresponding parental AAV capsid protein. In other embodiments, a subject rAAV virion capsid includes from 1 to about 25 amino acid insertions, deletions, or substitutions, compared to the parental AAV capsid protein, in addition to an insertion of from about 7 amino acids to about 10 amino acids in the GH loop or loop IV relative to a corresponding parental AAV capsid protein. For example, in some embodiments, a subject rAAV virion capsid includes from 1 to about 5, from about 5 to about 10, from about 10 to about 15, from about 15 to about 20, or from about 20 to about 25 amino acid insertions, deletions, or substitutions, compared to the parental AAV capsid protein, in addition to an insertion of from about 7 amino acids to about 10 amino acids in the GH loop or loop IV relative to a corresponding parental AAV capsid protein.

[00132] In some embodiments, a subject rAAV virion capsid does not include one, two, three, or four, of the following amino acid substitutions: Y273F, Y444F, Y500F, and Y730F.

[00133] In some embodiments, a subject variant capsid polypeptide comprises, in addition to an insertion peptide as described above, one, two, three, or four, of the following amino acid substitutions: Y273F, Y444F, Y500F, and Y730F.

[00134] In some embodiments, a subject rAAV virion capsid is a chimeric capsid, e.g., the capsid comprises a portion of an AAV capsid of a first AAV serotype and a portion of an AAV capsid of a second serotype; and comprises an insertion of from about 5 amino acids to about 11 amino acids in the GH loop or loop IV relative to a corresponding parental AAV capsid protein.

[00135] In some embodiments, a subject rAAV virion comprises a capsid protein comprising an amino acid sequence having at least about 85%, at least about 90%, at least about 95%, at least about 98%, or at least about 99%, amino acid sequence identity to the amino acid sequence provided in Figure 5; and an insertion of from about 5 amino acids to about 11 amino acids in the GH loop or loop IV relative to a corresponding parental AAV capsid protein.

[00136] In some embodiments, a subject rAAV virion comprises a capsid protein that includes a GH loop comprising an amino acid sequence having at least about 85%, at least about 90%, at least about 95%, at least about 98%, at least about 99%, or 100%, amino acid sequence identity to an amino acid sequence set forth in Figure 18A-C.

[00137] A subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of a retinal cell, compared to the infectivity of the retinal cell by an AAV virion comprising the corresponding parental AAV capsid protein.

[00138] In some cases, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of a retinal cell, when administered via intravitreal injection, compared to the infectivity of the retinal cell by an AAV virion comprising the corresponding parental AAV capsid protein, when administered via intravitreal injection.

[00139] In some embodiments, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of a photoreceptor (rod or cone) cell, compared to the infectivity of the photoreceptor cell by an AAV virion comprising the corresponding parental AAV capsid protein.

[00140] In some embodiments, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of a photoreceptor (rod or cone) cell, when administered via intravitreal injection, compared to the infectivity of the photoreceptor cell by an AAV virion comprising the corresponding parental AAV capsid protein, when administered via intravitreal injection.

[00141] In some embodiments, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of an RGC, compared to the infectivity of the RGC by an AAV virion comprising the corresponding parental AAV capsid protein.

[00142] In some embodiments, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of an RGC, when administered via intravitreal injection, compared to the infectivity of the RGC by an AAV virion comprising the corresponding parental AAV capsid protein, when administered via intravitreal injection.

[00143] In some embodiments, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of an RPE cell, compared to the infectivity of the RPE cell by an AAV virion comprising the corresponding parental AAV capsid protein.

[00144] In some embodiments, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of an RPE cell, when administered via intravitreal injection, compared to the infectivity of the RPE cell by an AAV virion comprising the corresponding parental AAV capsid protein, when administered via intravitreal injection.

[00145] In some embodiments, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of a Müller cell, compared to the infectivity of the Müller cell by an AAV virion comprising the corresponding parental AAV capsid protein.

[00146] In some embodiments, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of a Müller cell, when administered via intravitreal injection, compared to the

infectivity of the Müller cell by an AAV virion comprising the corresponding parental AAV capsid protein, when administered via intravitreal injection.

[00147] In some embodiments, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of a bipolar cell, compared to the infectivity of the bipolar cell by an AAV virion comprising the corresponding parental AAV capsid protein.

[00148] In some embodiments, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of a bipolar cell, when administered via intravitreal injection, compared to the infectivity of the bipolar cell by an AAV virion comprising the corresponding parental AAV capsid protein, when administered via intravitreal injection.

[00149] In some embodiments, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of an amacrine cell, compared to the infectivity of the amacrine cell by an AAV virion comprising the corresponding parental AAV capsid protein.

[00150] In some embodiments, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of an amacrine cell, when administered via intravitreal injection, compared to the infectivity of the amacrine cell by an AAV virion comprising the corresponding parental AAV capsid protein, when administered via intravitreal injection.

[00151] In some embodiments, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of a horizontal cell, compared to the infectivity of the horizontal cell by an AAV virion comprising the corresponding parental AAV capsid protein.

[00152] In some embodiments, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of a horizontal cell, when administered via intravitreal injection, compared to the infectivity of the horizontal cell by an AAV virion comprising the corresponding parental AAV capsid protein, when administered via intravitreal injection.

[00153] In some cases, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased ability to

cross the internal limiting membrane (ILM), compared to the ability of an AAV virion comprising the corresponding parental AAV capsid protein to cross the ILM.

[00154] In some cases, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased ability, when administered via intravitreal injection, to cross the internal limiting membrane (ILM), compared to the ability of an AAV virion comprising the corresponding parental AAV capsid protein to cross the ILM when administered via intravitreal injection.

[00155] A subject rAAV virion can cross the ILM, and can also traverse cell layers, including Müller cells, amacrine cells, etc., to reach the photoreceptor cells and or RPE cells. For example, a subject rAAV virion, when administered via intravitreal injection, can cross the ILM, and can also traverse cell layers, including Müller cells, amacrine cells, etc., to reach the photoreceptor cells and or RPE cells.

[00156] In some embodiments, a subject rAAV virion selectively infects a retinal cell, e.g., a subject rAAV virion infects a retinal cell with 10-fold, 15-fold, 20-fold, 25-fold, 50-fold, or more than 50-fold, specificity than a non-retinal cell, e.g., a cell outside the eye. For example, in some embodiments, a subject rAAV virion selectively infects a retinal cell, e.g., a subject rAAV virion infects a photoreceptor cell with 10-fold, 15-fold, 20-fold, 25-fold, 50-fold, or more than 50-fold, specificity than a non-retinal cell, e.g., a cell outside the eye.

[00157] In some embodiments, a subject rAAV virion selectively infects a photoreceptor cell, e.g., a subject rAAV virion infects a photoreceptor cell with 10-fold, 15-fold, 20-fold, 25-fold, 50-fold, or more than 50-fold, specificity than a non-photoreceptor cell present in the eye, e.g., a retinal ganglion cell, a Müller cell, etc.

[00158] In some embodiments, a subject rAAV virion exhibits at least 10-fold, at least 15-fold, at least 20-fold, at least 25-fold, at least 50-fold, or more than 50-fold, increased infectivity of a photoreceptor cell, when administered via intravitreal injection, compared to the infectivity of the photoreceptor cell by an AAV virion comprising the corresponding parental AAV capsid protein, when administered via intravitreal injection.

Gene products

[00159] A subject rAAV virion comprises a heterologous nucleic acid comprising a nucleotide sequence encoding a gene product. In some embodiments, the gene product is an interfering RNA. In some embodiments, the gene product is an aptamer. In some

embodiments, the gene product is a polypeptide. In some embodiments, the gene product is a site-specific nuclease that provide for site-specific knock-down of gene function.

Interfering RNA

[00160] Where the gene product is an interfering RNA (RNAi), suitable RNAi include RNAi that decrease the level of an apoptotic or angiogenic factor in a cell. For example, an RNAi can be an shRNA or siRNA that reduces the level of a gene product that induces or promotes apoptosis in a cell. Genes whose gene products induce or promote apoptosis are referred to herein as "pro-apoptotic genes" and the products of those genes (mRNA; protein) are referred to as "pro-apoptotic gene products." Pro-apoptotic gene products include, e.g., *Bax*, *Bid*, *Bak*, and *Bad* gene products. See, e.g., U.S. Patent No. 7,846,730.

[00161] Interfering RNAs could also be against an angiogenic product, for example VEGF (e.g., Cand5; see, e.g., U.S. Patent Publication No. 2011/0143400; U.S. Patent Publication No. 2008/0188437; and Reich et al. (2003) *Mol. Vis.* 9:210), VEGFR1 (e.g., Sirna-027; see, e.g., Kaiser et al. (2010) *Am. J. Ophthalmol.* 150:33; and Shen et al. (2006) *Gene Ther.* 13:225), or VEGFR2 (Kou et al. (2005) *Biochem.* 44:15064). See also, U.S. Patent Nos. 6,649,596, 6,399,586, 5,661,135, 5,639,872, and 5,639,736; and U.S. Patent Nos. 7,947,659 and 7,919,473.

Aptamers

[00162] Where the gene product is an aptamer, exemplary aptamers of interest include an aptamer against vascular endothelial growth factor (VEGF). See, e.g., Ng et al. (2006) *Nat. Rev. Drug Discovery* 5:123; and Lee et al. (2005) *Proc. Natl. Acad. Sci. USA* 102:18902. For example, a VEGF aptamer can comprise the nucleotide sequence 5'-cgcaaucagugaaugcuuauacauccg-3' (SEQ ID NO:17). Also suitable for use is a PDGF-specific aptamer, e.g., E10030; see, e.g., Ni and Hui (2009) *Ophthalmologica* 223:401; and Akiyama et al. (2006) *J. Cell Physiol.* 207:407).

Polypeptides

[00163] Where the gene product is a polypeptide, the polypeptide is generally a polypeptide that enhances function of a retinal cell, e.g., the function of a rod or cone photoreceptor cell, a retinal ganglion cell, a Müller cell, a bipolar cell, an amacrine cell, a horizontal cell, or a retinal pigmented epithelial cell. Exemplary polypeptides include neuroprotective polypeptides (e.g., GDNF, CNTF, NT4, NGF, and NTN); anti-

angiogenic polypeptides (e.g., a soluble vascular endothelial growth factor (VEGF) receptor; a VEGF-binding antibody; a VEGF-binding antibody fragment (e.g., a single chain anti-VEGF antibody); endostatin; tumstatin; angiostatin; a soluble Flt polypeptide (Lai et al. (2005) *Mol. Ther.* 12:659); an Fc fusion protein comprising a soluble Flt polypeptide (see, e.g., Pechan et al. (2009) *Gene Ther.* 16:10); pigment epithelium-derived factor (PEDF); a soluble Tie-2 receptor; etc.); tissue inhibitor of metalloproteinases-3 (TIMP-3); a light-responsive opsin, e.g., a rhodopsin; anti-apoptotic polypeptides (e.g., Bcl-2, Bcl-Xl); and the like. Suitable polypeptides include, but are not limited to, glial derived neurotrophic factor (GDNF); fibroblast growth factor 2; neurturin (NTN); ciliary neurotrophic factor (CNTF); nerve growth factor (NGF); neurotrophin-4 (NT4); brain derived neurotrophic factor (BDNF; e.g., a polypeptide comprising an amino acid sequence having at least about 90%, at least about 95%, at least about 98%, at least about 99%, or 100%, amino acid sequence identity to a contiguous stretch of from about 200 amino acids to 247 amino acids of the amino acid sequence depicted in Figure 11 (SEQ ID NO:11)); epidermal growth factor; rhodopsin; X-linked inhibitor of apoptosis; and Sonic hedgehog.

[00164] Suitable light-responsive opsins include, e.g., a light-responsive opsin as described in U.S. Patent Publication No. 2007/0261127 (e.g., ChR2; Chop2); U.S. Patent Publication No. 2001/0086421; U.S. Patent Publication No. 2010/0015095; and Diester et al. (2011) *Nat. Neurosci.* 14:387.

[00165] Suitable polypeptides also include retinoschisin (e.g., a polypeptide comprising an amino acid sequence having at least about 90%, at least about 95%, at least about 98%, at least about 99%, or 100%, amino acid sequence identity to a contiguous stretch of from about 200 amino acids to 224 amino acids of the amino acid sequence depicted in Figure 10 (SEQ ID NO:10). Suitable polypeptides include, e.g., retinitis pigmentosa GTPase regulator (RGPR)-interacting protein-1 (see, e.g., GenBank Accession Nos. Q96KN7, Q9EPQ2, and Q9GLM3) (e.g., a polypeptide comprising an amino acid sequence having at least about 90%, at least about 95%, at least about 98%, at least about 99%, or 100%, amino acid sequence identity to a contiguous stretch of from about 1150 amino acids to about 1200 amino acids, or from about 1200 amino acids to 1286 amino acids, of the amino acid sequence depicted in Figure 16 (SEQ ID NO:21); peripherin-2 (Prph2) (see, e.g., GenBank Accession No. NP_000313 (e.g., a polypeptide

comprising an amino acid sequence having at least about 90%, at least about 95%, at least about 98%, at least about 99%, or 100%, amino acid sequence identity to a contiguous stretch of from about 300 amino acids to 346 amino acids of the amino acid sequence depicted in Figure 14 (SEQ ID NO:19); and Travis et al. (1991) *Genomics* 10:733); peripherin (e.g., a polypeptide comprising an amino acid sequence having at least about 90%, at least about 95%, at least about 98%, at least about 99%, or 100%, amino acid sequence identity to a contiguous stretch of from about 400 amino acids to about 470 amino acids of the amino acid sequence depicted in Figure 15 (SEQ ID NO:20); a retinal pigment epithelium-specific protein (RPE65), (e.g., a polypeptide comprising an amino acid sequence having at least about 90%, at least about 95%, at least about 98%, at least about 99%, or 100%, amino acid sequence identity to a contiguous stretch of from about 200 amino acids to 247 amino acids of the amino acid sequence depicted in Figure 12 (SEQ ID NO:12)) (see, e.g., GenBank AAC39660; and Morimura et al. (1998) *Proc. Natl. Acad. Sci. USA* 95:3088); and the like.

[00166] Suitable polypeptides also include: CHM (choroidermia (Rab escort protein 1)), a polypeptide that, when defective or missing, causes choroideremia (see, e.g., Donnelly et al. (1994) *Hum. Mol. Genet.* 3:1017; and van Bokhoven et al. (1994) *Hum. Mol. Genet.* 3:1041); and Crumbs homolog 1 (CRB1), a polypeptide that, when defective or missing, causes Leber congenital amaurosis and retinitis pigmentosa (see, e.g., den Hollander et al. (1999) *Nat. Genet.* 23:217; and GenBank Accession No. CAM23328).

[00167] Suitable polypeptides also include polypeptides that, when defective or missing, lead to achromotopsia, where such polypeptides include, e.g., cone photoreceptor cGMP-gated channel subunit alpha (CNGA3) (see, e.g., GenBank Accession No. NP_001289; and Booij et al. (2011) *Ophthalmology* 118:160-167); cone photoreceptor cGMP-gated cation channel beta-subunit (CNGB3) (see, e.g., Kohl et al.(2005) *Eur J Hum Genet.* 13(3):302); guanine nucleotide binding protein (G protein), alpha transducing activity polypeptide 2 (GNAT2) (ACHM4); and ACHM5; and polypeptides that, when defective or lacking, lead to various forms of color blindness (e.g., L-opsin, M-opsin, and S-opsin). See Mancuso et al. (2009) *Nature* 461(7265):784–787.

Site-specific endonucleases

[00168] In some cases, a gene product of interest is a site-specific endonuclease that provide for site-specific knock-down of gene function, e.g., where the endonuclease

knocks out an allele associated with a retinal disease. For example, where a dominant allele encodes a defective copy of a gene that, when wild-type, is a retinal structural protein and/or provides for normal retinal function, a site-specific endonuclease can be targeted to the defective allele and knock out the defective allele.

[00169] In addition to knocking out a defective allele, a site-specific nuclease can also be used to stimulate homologous recombination with a donor DNA that encodes a functional copy of the protein encoded by the defective allele. Thus, e.g., a subject rAAV virion can be used to deliver both a site-specific endonuclease that knocks out a defective allele, and can be used to deliver a functional copy of the defective allele, resulting in repair of the defective allele, thereby providing for production of a functional retinal protein (e.g., functional retinoschisin, functional RPE65, functional peripherin, etc.). See, e.g., Li et al. (2011) *Nature* 475:217. In some embodiments, a subject rAAV virion comprises a heterologous nucleotide sequence that encodes a site-specific endonuclease; and a heterologous nucleotide sequence that encodes a functional copy of a defective allele, where the functional copy encodes a functional retinal protein. Functional retinal proteins include, e.g., retinoschisin, RPE65, retinitis pigmentosa GTPase regulator (RGPR)-interacting protein-1, peripherin, peripherin-2, and the like.

[00170] Site-specific endonucleases that are suitable for use include, e.g., zinc finger nucleases (ZFNs); and transcription activator-like effector nucleases (TALENs), where such site-specific endonucleases are non-naturally occurring and are modified to target a specific gene. Such site-specific nucleases can be engineered to cut specific locations within a genome, and non-homologous end joining can then repair the break while inserting or deleting several nucleotides. Such site-specific endonucleases (also referred to as "INDELs") then throw the protein out of frame and effectively knock out the gene. See, e.g., U.S. Patent Publication No. 2011/0301073.

Regulatory sequences

[00171] In some embodiments, a nucleotide sequence encoding a gene product of interest is operably linked to a constitutive promoter. In other embodiments, a nucleotide sequence encoding a gene product of interest is operably linked to an inducible promoter. In some instances, a nucleotide sequence encoding a gene product of interest is operably linked to a tissue-specific or cell type-specific regulatory element. For example, in some instances, a nucleotide sequence encoding a gene product of interest is

operably linked to a photoreceptor-specific regulatory element (e.g., a photoreceptor-specific promoter), e.g., a regulatory element that confers selective expression of the operably linked gene in a photoreceptor cell. Suitable photoreceptor-specific regulatory elements include, e.g., a rhodopsin promoter; a rhodopsin kinase promoter (Young et al. (2003) *Ophthalmol. Vis. Sci.* 44:4076); a beta phosphodiesterase gene promoter (Nicoud et al. (2007) *J. Gene Med.* 9:1015); a retinitis pigmentosa gene promoter (Nicoud et al. (2007) *supra*); an interphotoreceptor retinoid-binding protein (IRBP) gene enhancer (Nicoud et al. (2007) *supra*); an IRBP gene promoter (Yokoyama et al. (1992) *Exp Eye Res.* 55:225).

PHARMACEUTICAL COMPOSITIONS

[00172] The present disclosure provides a pharmaceutical composition comprising: a) a subject rAAV virion, as described above; and b) a pharmaceutically acceptable carrier, diluent, excipient, or buffer. In some embodiments, the pharmaceutically acceptable carrier, diluent, excipient, or buffer is suitable for use in a human.

[00173] Such excipients, carriers, diluents, and buffers include any pharmaceutical agent that can be administered without undue toxicity. Pharmaceutically acceptable excipients include, but are not limited to, liquids such as water, saline, glycerol and ethanol. Pharmaceutically acceptable salts can be included therein, for example, mineral acid salts such as hydrochlorides, hydrobromides, phosphates, sulfates, and the like; and the salts of organic acids such as acetates, propionates, malonates, benzoates, and the like. Additionally, auxiliary substances, such as wetting or emulsifying agents, pH buffering substances, and the like, may be present in such vehicles. A wide variety of pharmaceutically acceptable excipients are known in the art and need not be discussed in detail herein. Pharmaceutically acceptable excipients have been amply described in a variety of publications, including, for example, A. Gennaro (2000) "Remington: The Science and Practice of Pharmacy," 20th edition, Lippincott, Williams, & Wilkins; Pharmaceutical Dosage Forms and Drug Delivery Systems (1999) H.C. Ansel et al., eds., 7th ed., Lippincott, Williams, & Wilkins; and Handbook of Pharmaceutical Excipients (2000) A.H. Kibbe et al., eds., 3rd ed. Amer. Pharmaceutical Assoc.

METHODS OF DELIVERING A GENE PRODUCT TO A RETINAL CELL AND TREATMENT METHODS

[00174] The present disclosure provides a method of delivering a gene product to a retinal cell in an individual, the method comprising administering to the individual a subject rAAV virion as described above. The gene product can be a polypeptide or an interfering RNA (e.g., an shRNA, an siRNA, and the like), an aptamer, or a site-specific endonuclease, as described above. Delivering a gene product to a retinal cell can provide for treatment of a retinal disease. The retinal cell can be a photoreceptor, a retinal ganglion cell, a Müller cell, a bipolar cell, an amacrine cell, a horizontal cell, or a retinal pigmented epithelial cell. In some cases, the retinal cell is a photoreceptor cell, e.g., a rod or cone cell.

[00175] The present disclosure provides a method of treating a retinal disease, the method comprising administering to an individual in need thereof an effective amount of a subject rAAV virion as described above. A subject rAAV virion can be administered via intraocular injection, by intravitreal injection, or by any other convenient mode or route of administration. Other convenient modes or routes of administration include, e.g., intravenous, intranasal, etc.

[00176] A "therapeutically effective amount" will fall in a relatively broad range that can be determined through experimentation and/or clinical trials. For example, for in vivo injection, i.e., injection directly into the eye, a therapeutically effective dose will be on the order of from about 10^6 to about 10^{15} of the rAAV virions, e.g., from about 10^8 to 10^{12} rAAV virions. For *in vitro* transduction, an effective amount of rAAV virions to be delivered to cells will be on the order of from about 10^8 to about 10^{13} of the rAAV virions. Other effective dosages can be readily established by one of ordinary skill in the art through routine trials establishing dose response curves.

[00177] In some embodiments, more than one administration (e.g., two, three, four or more administrations) may be employed to achieve the desired level of gene expression over a period of various intervals, e.g., daily, weekly, monthly, yearly, etc.

[00178] Ocular diseases that can be treated using a subject method include, but are not limited to, acute macular neuroretinopathy; Behcet's disease; choroidal neovascularization; diabetic uveitis; histoplasmosis; macular degeneration, such as acute macular degeneration, non-exudative age related macular degeneration and exudative

age related macular degeneration; edema, such as macular edema, cystoid macular edema and diabetic macular edema; multifocal choroiditis; ocular trauma which affects a posterior ocular site or location; ocular tumors; retinal disorders, such as central retinal vein occlusion, diabetic retinopathy (including proliferative diabetic retinopathy), proliferative vitreoretinopathy (PVR), retinal arterial occlusive disease, retinal detachment, uveitic retinal disease; sympathetic opthalmia; Vogt Koyanagi-Harada (VKH) syndrome; uveal diffusion; a posterior ocular condition caused by or influenced by an ocular laser treatment; posterior ocular conditions caused by or influenced by a photodynamic therapy; photocoagulation, radiation retinopathy; epiretinal membrane disorders; branch retinal vein occlusion; anterior ischemic optic neuropathy; non-retinopathy diabetic retinal dysfunction; retinoschisis; retinitis pigmentosa; glaucoma; Usher syndrome, cone-rod dystrophy; Stargardt disease (fundus flavimaculatus); inherited macular degeneration; chorioretinal degeneration; Leber congenital amaurosis; congenital stationary night blindness; choroideremia; Bardet-Biedl syndrome; macular telangiectasia; Leber's hereditary optic neuropathy; retinopathy of prematurity; and disorders of color vision, including achromatopsia, protanopia, deuteranopia, and tritanopia.

NUCLEIC ACIDS AND HOST CELLS

[00179] The present disclosure provides an isolated nucleic acid comprising a nucleotide sequence that encodes a subject variant adeno-associated virus (AAV) capsid protein as described above, where the variant AAV capsid protein comprises an insertion of from about 5 amino acids to about 11 amino acids in the GH loop or loop IV relative to a corresponding parental AAV capsid protein, and where the variant capsid protein, when present in an AAV virion, provides for increased infectivity of a retinal cell compared to the infectivity of the retinal cell by an AAV virion comprising the corresponding parental AAV capsid protein. A subject isolated nucleic acid can be an AAV vector, e.g., a recombinant AAV vector.

Insertion peptides

[00180] A variant AAV capsid protein encoded by a subject nucleic acid has an insertion peptide of from about 5 amino acids to about 11 amino acids in length is inserted into the GH loop of an AAV capsid. The insertion peptide has a length of 5 amino acids, 6 amino acids, 7 amino acids, 8 amino acids, 9 amino acids, 10 amino acids, or 11 amino acids.

[00181] The insertion peptide can comprise an amino acid sequence of any one of the formulas set forth below.

[00182] For example, an insertion peptide can be a peptide of from 5 to 11 amino acids in length, where the insertion peptide is of **Formula I:**

[00183] $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$

[00184] where:

each of Y_1 –Y_4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X_1, if present, is selected from Leu, Asn, and Lys;

X_2 is selected from Gly, Glu, Ala, and Asp;

X_3 is selected from Glu, Thr, Gly, and Pro;

X_4 is selected from Thr, Ile, Gln, and Lys;

X_5 is selected from Thr and Ala;

X_6 is selected from Arg, Asn, and Thr;

X_7, if present, is selected from Pro and Asn.

[00185] As another example, an insertion peptide can be a peptide of from 5 to 11 amino acids in length, where the insertion peptide is of **Formula IIa:**

[00186] $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$

[00187] where:

each of Y_1 –Y_4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

each of X_1 – X_4 is any amino acid;

X_5 is Thr;

X_6 is Arg; and

X_7 is Pro.

[00188] As another example, an insertion peptide can be a peptide of from 5 to 11 amino acids in length, where the insertion peptide is of **Formula IIb:**

[00189] $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$

[00190] where:

each of Y_1 –Y_4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X_1, if present, is selected from Leu and Asn;

X_2, if present, is selected from Gly and Glu;

X_3 is selected from Glu and Thr;

X_4 is selected from Thr and Ile;

X_5 is Thr;

X_6 is Arg; and

X_7 is Pro.

[00191] As another example, an insertion peptide can be a peptide of from 5 to 11 amino acids in length, where the insertion peptide is of **Formula III:**

[00192] $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$

[00193] where:

each of Y_1 –Y_4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X_1, if present, is Lys;

X_2 is selected from Ala and Asp;

X_3 is selected from Gly and Pro;

X_4 is selected from Gln and Lys;

X_5 is selected from Thr and Ala;

X_6 is selected from Asn and Thr;

X_7, if present, is Asn.

[00194] As another example, an insertion peptide can be a peptide of from 5 to 11 amino acids in length, where the insertion peptide is of **Formula IV:**

[00195] $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$

[00196] where:

each of Y_1 –Y_4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X_1, if present, is a positively charged amino acid or an uncharged amino acid; or is selected from Leu, Asn, Arg, Ala, Ser, and Lys;

X_2 is a negatively charged amino acid or an uncharged amino acid; or is selected from Gly, Glu, Ala, Val, Thr, and Asp;

X_3 is a negatively charged amino acid or an uncharged amino acid; or is selected from Glu, Thr, Gly, Asp, or Pro;

X_4 is selected from Thr, Ile, Gly, Lys, Asp, and Gln;

X_5 is a polar amino acid, an alcohol (an amino acid having a free hydroxyl group), or a hydrophobic amino acid; or is selected from Thr, Ser, Val, and Ala;

X_6 is a positively charged amino acid or an uncharged amino acid; or is selected from Arg, Val, Lys, Pro, Thr, and Asn; and

X_7, if present, is a positively charged amino acid or an uncharged amino acid; or is selected from Pro, Gly, Phe, Asn, and Arg.

[00197] As non-limiting examples, the insertion peptide can comprise an amino acid sequence selected from LGETTRP (SEQ ID NO:13), NETITRP (SEQ ID NO:14), KAGQANN (SEQ ID NO:15), KDPKTTN (SEQ ID NO:16), KDTDTTR (SEQ ID NO:57), RAGGSVG (SEQ ID NO:58), AVDTTKF (SEQ ID NO:59), and STGKVPN (SEQ ID NO:60).

[00198] In some cases, the insertion peptide has from 1 to 4 spacer amino acids (Y_1-Y_4) at the amino terminus and/or at the carboxyl terminus of any one of LGETTRP (SEQ ID NO:13), NETITRP (SEQ ID NO:14), KAGQANN (SEQ ID NO:15), KDPKTTN (SEQ ID NO:16), KDTDTTR (SEQ ID NO:57), RAGGSVG (SEQ ID NO:58), AVDTTKF (SEQ ID NO:59), and STGKVPN (SEQ ID NO:60). Suitable spacer amino acids include, but are not limited to, leucine, alanine, glycine, and serine.

[00199] For example, in some cases, an insertion peptide has one of the following amino acid sequences: LALGETTRPA (SEQ ID NO:45); LANETITRPA (SEQ ID NO:46), LAKAGQANNA (SEQ ID NO:47), LAKDPKTTNA (SEQ ID NO:48), LAKDTDTTRA (SEQ ID NO:61), LARAGGSVGA (SEQ ID NO:62), LAAVDTTKFA (SEQ ID NO:63), and LASTGKVPNA (SEQ ID NO:64). As another example, in some cases, an insertion peptide has one of the following amino acid sequences: AALGETTRPA (SEQ ID NO:49); AANETITRPA (SEQ ID NO:50), AAKAGQANNA (SEQ ID NO:51), and AAKDPKTTNA (SEQ ID NO:52). As yet another example, in some cases, an insertion peptide has one of the following amino acid sequences: GLGETTRPA (SEQ ID NO:53); GNETITRPA (SEQ ID NO:54), GKAGQANNA (SEQ ID NO:55), and GKDPKTTNA (SEQ ID NO:56). As another example, in some cases, an insertion peptide comprises one of KDTDTTR (SEQ ID NO:57), RAGGSVG (SEQ ID NO:58), AVDTTKF (SEQ ID NO:59), and STGKVPN (SEQ ID NO:60), flanked on the C-terminus by AA and on the N-terminus by A; or comprises one of KDTDTTR (SEQ ID NO:57), RAGGSVG (SEQ ID NO:58), AVDTTKF (SEQ ID NO:59), and STGKVPN (SEQ ID NO:60) flanked on the C-terminus by G and on the N-terminus by A.

[00200] A subject recombinant AAV vector can be used to generate a subject recombinant AAV virion, as described above. Thus, the present disclosure provides a

recombinant AAV vector that, when introduced into a suitable cell, can provide for production of a subject recombinant AAV virion.

[00201] The present invention further provides host cells, e.g., isolated (genetically modified) host cells, comprising a subject nucleic acid. A subject host cell can be an isolated cell, e.g., a cell in *in vitro* culture. A subject host cell is useful for producing a subject rAAV virion, as described below. Where a subject host cell is used to produce a subject rAAV virion, it is referred to as a "packaging cell." In some embodiments, a subject host cell is stably genetically modified with a subject nucleic acid. In other embodiments, a subject host cell is transiently genetically modified with a subject nucleic acid.

[00202] A subject nucleic acid is introduced stably or transiently into a host cell, using established techniques, including, but not limited to, electroporation, calcium phosphate precipitation, liposome-mediated transfection, and the like. For stable transformation, a subject nucleic acid will generally further include a selectable marker, e.g., any of several well-known selectable markers such as neomycin resistance, and the like.

[00203] A subject host cell is generated by introducing a subject nucleic acid into any of a variety of cells, e.g., mammalian cells, including, e.g., murine cells, and primate cells (e.g., human cells). Suitable mammalian cells include, but are not limited to, primary cells and cell lines, where suitable cell lines include, but are not limited to, 293 cells, COS cells, HeLa cells, Vero cells, 3T3 mouse fibroblasts, C3H10T1/2 fibroblasts, CHO cells, and the like. Non-limiting examples of suitable host cells include, e.g., HeLa cells (e.g., American Type Culture Collection (ATCC) No. CCL-2), CHO cells (e.g., ATCC Nos. CRL9618, CCL61, CRL9096), 293 cells (e.g., ATCC No. CRL-1573), Vero cells, NIH 3T3 cells (e.g., ATCC No. CRL-1658), Huh-7 cells, BHK cells (e.g., ATCC No. CCL10), PC12 cells (ATCC No. CRL1721), COS cells, COS-7 cells (ATCC No. CRL1651), RAT1 cells, mouse L cells (ATCC No. CCLI.3), human embryonic kidney (HEK) cells (ATCC No. CRL1573), HLHepG2 cells, and the like. A subject host cell can also be made using a baculovirus to infect insect cells such as Sf9 cells, which produce AAV (see, e.g., U.S. Patent No. 7,271,002; US patent application 12/297,958)

[00204] In some embodiments, a subject genetically modified host cell includes, in addition to a nucleic acid comprising a nucleotide sequence encoding a variant AAV capsid protein, as described above, a nucleic acid that comprises a nucleotide sequence

encoding one or more AAV rep proteins. In other embodiments, a subject host cell further comprises an rAAV vector. An rAAV virion can be generated using a subject host cell. Methods of generating an rAAV virion are described in, e.g., U.S. Patent Publication No. 2005/0053922 and U.S. Patent Publication No. 2009/0202490.

EXAMPLES

[00205] The following examples are put forth so as to provide those of ordinary skill in the art with a complete disclosure and description of how to make and use the present invention, and are not intended to limit the scope of what the inventors regard as their invention nor are they intended to represent that the experiments below are all or the only experiments performed. Efforts have been made to ensure accuracy with respect to numbers used (e.g. amounts, temperature, etc.) but some experimental errors and deviations should be accounted for. Unless indicated otherwise, parts are parts by weight, molecular weight is weight average molecular weight, temperature is in degrees Celsius, and pressure is at or near atmospheric. Standard abbreviations may be used, e.g., bp, base pair(s); kb, kilobase(s); pl, picoliter(s); s or sec, second(s); min, minute(s); h or hr, hour(s); aa, amino acid(s); kb, kilobase(s); bp, base pair(s); nt, nucleotide(s); i.m., intramuscular(ly); i.p., intraperitoneal(ly); s.c., subcutaneous(ly); and the like.

Example 1: AAV variant with enhanced transduction of retinal cells

[00206] The approach used was to create a peptide display library by introducing a unique *Avr*II site into the wild type AAV2 genome between amino acid 587 and 588 by polymerase chain reaction (PCR) mutagenesis. A random 21 nucleotide insert, 7mer For, was used to synthesize dsDNA inserts, along with the antisense primer 7mer Rev. The resulting dsDNA inserts were cloned into the *Avr*II site of the genome after digestion with *Nhe*I, producing a diverse 7mer display library which was then packaged (Perabo et al., 2003; Muller et al., 2003). The virus was generated such that each viral genome was packaged or encapsidated within the capsid protein variant that that genome encoded. In this respect, functional improvements identified through selection can be linked to the genome sequence encoding this improved function contained within the viral capsid.

[00207] This library was subjected to positive selection within rho-GFP mice (Wensel et al. (2005) *Vision Res.* 45:3445). Briefly, in one round of selection, adult rho-GFP mice

were intravitreally injected with 2μL of phosphate buffered saline (PBS)-dialyzed, iodixanol-purified library with a genomic titer of approximately $1x10^{12}$ viral genomes (vg)/mL. An ultrafine 30 1/2-gauge disposable needle was passed through the sclera of the animal's eye, at the equator and next to the limbus, into the vitreous cavity. Injection of 2μl of virus was made with direct observation of the needle in the center of the vitreous cavity. One week post-injection, eyes were enucleated and retinas dissociated using a light, papain protease treatment, followed by fluorescence activated cell sorter (FACS) isolation of photoreceptor populations. Successful virions were then PCR amplified from subsequent genomic extractions and further cloned and repackaged for injection.

[00208] Further iterations of this selection were performed, narrowing the pool of variants to a subset with the most permissive mutations. After three iterations, a round of error-prone PCR was performed to create a further generation of variants for selection. In total, this process was repeated for two generations. In this respect, this process of directed evolution created photoreceptor-permissive AAV variants through the application of positive selection and induced mutagenesis, similar to the process of natural evolution.

[00209] Subsequently, the cap genes of fifty variants were sequenced to determine the most prominent and successful variants to have permissive mutations for intravitreal photoreceptor transduction. Of the 50 clones, 46 gave readable sequences of a 7mer insert. Remarkably, nearly two thirds of clones contained the same distinct 7mer motif (~^{588}LGETTRP~; SEQ ID NO:13). Interestingly, the next most prominent variant (~^{588}NETITRP~; SEQ ID NO:14) also contained a similar flanking motif consisting of a positively-charged arginine residue in between a polar threonine and a nonpolar proline residue (TRP).

Table 1

Clone	Appr. Frequency (%)	Frequency
~^{588}LGETTRP~ (SEQ ID NO:13)	64	31
~^{588}NETITRP~ (SEQ ID NO:14)	12	5
~^{588}KAGQANN~ (SEQ ID NO:15)	6	3
~^{588}KDPKTTN~ (SEQ ID NO:16)	4	2
~^{588}KDTDTTR (SEQ ID NO:57)		2
~^{588}RAGGSVG (SEQ ID NO:58)		1
~^{588}AVDTTKF (SEQ ID NO:59)		1
~^{588}STGKVPN (SEQ ID NO:60)		1

[00210] *Table 1* Sequencing of isolated variants from directed evolution reveals a high degree of convergence in viral libraries. All variants derived from the AAV2 7mer library, with approximately 64% of variants containing the same 7mer motif (~^{588}LGETTRP~ (SEQ ID NO:13)).

[00211] Among the 7mer insert sequences, there were moderate preferences at particular positions, e.g., a positively charged amino acid at position 1; a negatively charged amino acid at position 2; an alcohol (e.g., an amino acid having an alcohol group (a free hydroxyl group), such as Thr or Ser) at position 5.

[00212] The 7mer inserts were flanked by spacers, as shown in Table 2:

Clone	Frequency
~^{588}LALGETTRPA~ (SEQ ID NO:45)	31
~^{588}LANETITRPA~ (SEQ ID NO:46)	5
~^{588}LAKAGQANNA~ (SEQ ID NO:47)	3
~^{588}LAKDPKTTNA~ (SEQ ID NO:48)	2
~^{588}LAKDTDTTRA~ (SEQ ID NO:61)	2
~^{588}LARAGGSVGA~ (SEQ ID NO:62)	1
~^{588}LAAVDTTKFA~ (SEQ ID NO:63)	1
~^{588}LASTGKVPNA~ (SEQ ID NO:64)	1

[00213] *Figure 1.* Representative three-dimensional capsid model of AAV2 containing a random heptamer (shown in orange) following amino acid 587. This area of the AAV2 capsid likely participates in cell-surface receptor binding.

[00214] In light of the high degree of library convergence from the above-described selection, a recombinant form of AAV2 ~^{588}LGETTRP~ (SEQ ID NO:13; nick named 7M8) was cloned and packaged the vector with a scCAG-GFP transgene to visualize its transduction profile. Three weeks following intravitreal injection in adult mice, robust

expression in numerous cell types, including retinal ganglion cells (RGCs) and Müller cells, was observed. Importantly, transduction of photoreceptors in retinas injected with 7M8, as seen by GFP expression in outer nuclear layer (ONL) nuclei (red arrows) and in outer segments (Figure 2, blue arrow), was observed, whereas AAV2 showed no discernable photoreceptor expression.

[00215] *Figure 2* AAV2 7M8 variant (right) demonstrates greater levels of intravitreal photoreceptor transduction relative to AAV2 (left). Confocal microscopy of transverse retinal sections three weeks after intravitreal injection of 2μL of $1x10^{12}$ vg/mL of AAV2 7M8 and AAV2 scCAG GFP in adult mice. Red arrows (top) denote photoreceptor nuclei and blue arrow (top) denote photoreceptor outer segments.

[00216] In light of these gains in retinal cell transduction, an attempt was made to increase specificity in expression through the use of a ssRho-eGFP transgene containing a photoreceptor-specific rhodopsin promoter to better resolve transduction efficiencies specifically in photoreceptors (Figure 3). Indeed the use of a photoreceptor specific Rho promoter limited the GFP expression to the photoreceptors. An attempt was made to improve 7M8 transduction efficiency by combining a rational design approach to the previous directed evolution approach. Therefore, four surface exposed tyrosine residues were mutagenized to phenylalanines on the 7M8 capsid (Y273F, Y444F, Y500F, and Y730F) which has previous been shown to increase photoreceptor infectivity (Petrs-Silva et al., 2009). Interestingly, the addition of mutations decreased number of photoreceptors transduced compared to the original virus as show by FACs sorting of the GFP(+) photoreceptors from 7m8 or 7m8-4YF infected retinas (Figure 4).

[00217] *Figure 3.* Representative fluorescence images of retinal cryoslices showing GFP expression resulting from 7m8 carrying the GFP gene under the control of the ubiquitous CAG promoter (left) or a photoreceptor specific Rho promoter (right).

[00218] *Figure 4.* GFP(+) photoreceptor cells per million retinal cells as counted by flow cytometry. 7m8 transduces more than 2x the amount of photoreceptors compared 7m8 bearing 4 tyrosine mutations (top).

Example 2: Treatment of retinoschisis

[00219] Using the expression construct 7m8-rho-RS1, a functional retinoschisin (RS1) protein was delivered to retinoschisin-deficient mice (Rs1h-deficient mice; Rs1h is the mouse homolog of human RS1). The vector comprises a nucleotide sequence encoding a

functional retinoschisin protein under transcriptional control of a rhodopsin promoter. See Figures 13A-C, where the bold and underlined nucleotide sequence (nucleotides 4013-4851) are the rhodopsin promoter; and nucleotides 4866-5540 (with the start atg and stop tga sequences shown in bold) encode a human RS1 protein.

[00220] The 7m8-rho-RS1 construct was administered intravitreally to Rs1h-/- mice at P15. Rs1h-/- mice were generated through targeted disruption of exon 3 of the Rs1h gene, as described (Weber et al. (2002) *Proc. Natl. Acad. Sci. USA* 99:6222). The Rs1h-/- mice are deficient in the Rs1h protein product, have an electronegative ERG (e.g., a reduced b-wave with relative preservation of the a-wave) and splitting of the layers of the retina, similar to what is seen in human retinoschisis patients. Injection of the 7m8-rho-RS1 vector into the Rs1h-/- led to high levels of panretinal RS1 expression from photoreceptors in the retina. RS1 expression led to improved retinal morphology with a decrease in the number and size of cavities in the retina as seen in spectral-domain optical coherence tomography (SD-OCT) imaging (Figures 7A-I), a rescue of the ERG b-wave (Figures 8A-D), and long-term structural preservation of the retina (Figures 9A-E).

[00221] Figures 7A-I. Representative high-resolution SD-OCT images of retinas injected with 7m8-rho-GFP (left column), 7m8-rho-RS1 (middle column), or uninjected WT animals (right column). Fundus images were taken through the inner nuclear layer of the superior retina and exclude other layers (a-c). Transverse images of the superior (d-f) and inferior (g-i) retina were taken using the optic nerve head as a landmark.

[00222] The untreated RS1 retina increases in overall thickness when measured from the inner limiting membrane (ILM) to the photoreceptors, as the pathology progresses due to the schisis splitting the inner retina. This process is distinct from that observed in most retinal degenerative diseases (RDD) which do not form schisis, but exhibit progressive photoreceptor cell death in the INL and concomitant retinal thinning and loss of ERG amplitude. In RS1, the ONL thins as photoreceptors die from the disease, but this is distinct from the overall retinal thickness change. It is generally thought that a successful therapy for RS1 would return the overall retinal thickness to the wildtype and ameliorate the photoreceptor loss in the ONL. In most RDD other than Rs1, the loss of photoreceptors, marked by ONL thinning, is paralleled by a decrease in retinal physiological output as measured by the ERG amplitude. RS1 is one of the very few

examples of a retinal disease in which the pathology increases the retinal thickness with concomitant erg amplitude loss. In summary, restoring the RS1 gene product, an extracellular retinal "glue; - thins the retina back to the wildtype thickness and the erg amplitude returns to near normal levels as the schisis resolves.

[00223] Figure 8a shows a comparison of functional rescue of untreated Rs1-/- eyes to AAV2-rho-RS1, 7m8-rho-GFP, and 7m8-rho-RS1 injected eyes both one month (left) and 4 months (right) after injection. One month post-injection, 7m8-rho-RS1 led to considerable rescue of the ERG b-wave amplitude, whereas AAV2-rho.RS1 was statistically indistinguishable from untreated eyes.

[00224] After 4 months, the 7m8-rho-RS1 amplitude further increases toward the wild-type amplitude (right). Figure 8b shows representative ERG traces from 7m8-rho-RS1-injected eyes show improved amplitude of the a-wave and b-wave and a waveform closer to wild-type eyes, compared to 7m8-rho-GFP-injected eyes. Figure 8c shows the amplitude of the full-field scotopic b-wave resulting from a high intensity (1 log cd x s/m2) stimulus was recorded on a monthly basis beginning one month after injection at P15 for each condition. Three responses were recorded and averaged for each eye at each time point.

[00225] Mean ERG b-wave amplitudes were plotted as a function of time post-injection. n=7 was used for both conditions. Figure 8d shows an analysis of ERG responses under scotopic (upper traces, stimulus range from -3 to 1 log cd x s/m2) and photopic (lower traces, range from -0.9 to 1.4 log cd x s/m2) conditions indicates improved rod and cone function over a range of stimuli intensities.

[00226] Figures 9A-E. Sustained improvements in retinal thickness measured at 10 months post 7m8-rho-RS1 treatment. Representative transverse SD-OCT images of a) 7m8-rho-RS1 or b) or 7m8-rho-GFP treated retinas 10 months post-injection centered on the optic nerve head. Measurements of c) retinal thickness, d) ONL thickness, and e) and inner and outer segment thickness are plotted as a function of distance from the optic nerve head.

Example 3: AAV variant used to deliver a protein to retinal cells in the macaque

[0001] A recombinant AAV2 virion (7m8 carrying GFP under the control of a connexin36 promoter) was generated. The recombinant AAV2 virion included an AAV2 capsid variant with an insertion of LALGETTRPA peptide between amino acids 587 and 588 of

AAV2 capsid, and GFP under transcriptional control of a connexin36 promoter, which is expressed in interneurons. The rAAV2 virion was injected intravitreally into the eye of a macaque. The data are shown in Figure 18.

[0002] Figure 18 provides a fluorescence fundus image showing GFP expression at the back of the retina 9 weeks after administration of 7m8 carrying GFP under the control of a connexin36 promoter. Compared to the parental AAV2 serotype (Yin et al, IOVS 52(5); 2775), a higher level of expression was seen in the foveal ring, and visible fluorescence was seen in the central retina outside the fovea.

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[0019] While the present invention has been described with reference to the specific embodiments thereof, it should be understood by those skilled in the art that various changes may be made and equivalents may be substituted without departing from the true spirit and scope of the invention. In addition, many modifications may be made to adapt a particular situation, material, composition of matter, process, process step or steps, to the objective, spirit and scope of the present invention. All such modifications are intended to be within the scope of the claims appended hereto.

Claims

What is claimed is:

1. A recombinant adeno-associated virus (rAAV) virion comprising:

a) a variant AAV capsid protein, wherein the variant AAV capsid protein comprises a peptide insertion relative to a corresponding parental AAV capsid protein, wherein the insertion site is located between two adjacent amino acids at a position between amino acids 570 and 611 of VP1 of AAV2 or the corresponding position in the capsid protein of another AAV serotype, wherein the peptide insertion is a peptide of Formula I, Formula IIa, Formula IIb, Formula III, or Formula IV, and wherein the AAV variant capsid protein confers increased infectivity of a retinal cell compared to the infectivity of the retinal cell by an AAV virion comprising the corresponding parental AAV capsid protein, wherein:

i) Formula I is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu, Asn, and Lys;

X2 is selected from Gly, Glu, Ala, and Asp;

X3 is selected from Glu, Thr, Gly, and Pro;

X4 is selected from Thr, Ile, Gln, and Lys;

X5 is selected from Thr and Ala;

X6 is selected from Arg, Asn, and Thr; and

X7, if present, is selected from Pro and Asn;

ii) Formula IIa is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

each of X1 – X4 is any amino acid;

X5 is Thr;

X6 is Arg; and

X7 is Pro;

iii) Formula IIb is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu and Asn;

X2, if present, is selected from Gly and Glu;

X3 is selected from Glu and Thr;

X4 is selected from Thr and Ile;

X5 is Thr;

X6 is Arg; and

X7 is Pro;

iv) Formula III is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is Lys;

X2 is selected from Ala and Asp;

X3 is selected from Gly and Pro;

X4 is selected from Gln and Lys;

X5 is selected from Thr and Ala;

X6 is selected from Asn and Thr; and

X7, if present, is Asn; and

v) Formula IV is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu, Asn, Arg, Ala, Ser, and Lys;

X2 is selected from Gly, Glu, Ala, Val, Thr, and Asp;

X3 is selected from Glu, Thr, Gly, Asp, or Pro;

X4 is selected from Thr, Ile, Gly, Lys, Asp, and Gln;

X5 is selected from Thr, Ser, Val, and Ala;

X6 is selected from Arg, Val, Lys, Pro, Thr, and Asn; and

X7 is selected from Pro, Gly, Phe, Asn, and Arg; and

b) a heterologous nucleic acid comprising a nucleotide sequence encoding a gene product.

2. The rAAV virion of claim 1, wherein the insertion comprises an amino acid sequence selected from LGETTRP (SEQ ID NO:13), NETITRP (SEQ ID NO:14), KAGQANN (SEQ ID NO:15), KDPKTTN (SEQ ID NO:16), KDTDTTR (SEQ ID NO:57), RAGGSVG (SEQ ID NO:58), AVDTTKF (SEQ ID NO:59), and STGKVPN (SEQ ID NO:60).

3. The rAAV virion of claim 1, wherein the retinal cell is a photoreceptor, a retinal ganglion cell, a Müller cell, a bipolar cell, an amacrine cell, a horizontal cell, or a retinal pigmented epithelium cell.

4. The rAAV virion of claim 1, wherein the insertion site is between amino acids 587 and 588 of the AAV2 capsid protein or the corresponding position in the capsid protein of another AAV serotype.

5. The rAAV virion of claim 1, wherein the insertion site is between amino acids 587 and 588 of the AAV2 capsid protein or the corresponding position in the capsid protein of another AAV serotype.

6. The rAAV virion of claim 5, wherein the insertion site is between amino acids 587 and 588 of AAV2.

7. The rAAV virion of claim 6, wherein the insertion comprises the amino acid sequence LGETTRP (SEQ ID NO:13).

8. The rAAV virion of claim 1, wherein the rAAV virion exhibits at least 10-fold increased infectivity of a retinal cell compared to the infectivity of the retinal cell by an AAV virion comprising the corresponding parental AAV capsid protein.

9. The rAAV virion of claim 1, wherein the rAAV virion exhibits at least 50-fold increased infectivity of a retinal cell compared to the infectivity of the retinal cell by an AAV virion comprising the corresponding parental AAV capsid protein.

10. The rAAV virion of claim 1, wherein gene product is an interfering RNA or an aptamer.

11. The rAAV virion of claim 1, wherein the gene product is a polypeptide.

12. The rAAV virion of claim 11, wherein the polypeptide is a neuroprotective polypeptide, an anti-angiogenic polypeptide, or a polypeptide that enhances function of a retinal cell.

13. A pharmaceutical composition comprising:

a) a recombinant adeno-associated virus virion of any one of claims 1-12; and

b) a pharmaceutically acceptable excipient.

14. Use of a recombinant adeno-associated virus (rAAV) virion according to any one of claims 1-12 in the manufacture of a medicament for delivering a gene product to a retinal cell in an individual.

15. Use of claim 14, wherein the gene product is a polypeptide.

16. Use of claim 14, wherein the gene product is a short interfering RNA or an aptamer.

17. Use of claim 15, wherein the polypeptide is a neuroprotective factor, an anti-angiogenic polypeptide, an anti-apoptotic factor, or a polypeptide that enhances function of a retinal cell.

18. Use of claim 15, wherein the polypeptide is glial derived neurotrophic factor, fibroblast growth factor 2, neurturin, ciliary neurotrophic factor, nerve growth factor, brain derived neurotrophic factor, epidermal growth factor, rhodopsin, X-linked inhibitor of apoptosis, retinoschisin, RPE65, retinitis pigmentosa GTPase-interacting protein-1, peripherin, peripherin-2, a rhodopsin, or Sonic hedgehog.

19. Use of a recombinant adeno-associated virus (rAAV) virion according to any one of claims 1-12 in the manufacture of a medicament for treating a retinal disease in an individual.

20. Use of claim 19, wherein the medicament is for intraocular injection.

21. Use of claim 19, wherein the medicament is for intravitreal injection.

22. Use of claim 19, wherein the ocular disease is glaucoma, retinitis pigmentosa, macular degeneration, retinoschisis, Leber's Congenital Amaurosis, diabetic retinopathy, achromotopsia, or color blindness.

23. An isolated nucleic acid comprising a nucleotide sequence that encodes a variant adeno-associated virus (AAV) capsid protein, wherein the variant AAV capsid protein comprises a peptide insertion relative to a corresponding parental AAV capsid protein,

wherein the insertion site is located between two adjacent amino acids at a position between amino acids 570 and 611 of VP1 of AAV2 or the corresponding position in the capsid protein of another AAV serotype,

wherein the peptide insertion is a peptide of Formula I, Formula IIa, Formula IIb, Formula III, or Formula IV, wherein:

i) Formula I is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu, Asn, and Lys;

X2 is selected from Gly, Glu, Ala, and Asp;

X3 is selected from Glu, Thr, Gly, and Pro;

X4 is selected from Thr, Ile, Gln, and Lys;

X5 is selected from Thr and Ala;

X6 is selected from Arg, Asn, and Thr; and

X7, if present, is selected from Pro and Asn;

ii) Formula IIa is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

each of X1 – X4 is any amino acid;

X5 is Thr;

X6 is Arg; and

X7 is Pro;

iii) Formula IIb is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu and Asn;

X2, if present, is selected from Gly and Glu;

X3 is selected from Glu and Thr;

X4 is selected from Thr and Ile;

X5 is Thr;

X6 is Arg; and

X7 is Pro;

iv) Formula III is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is Lys;

X2 is selected from Ala and Asp;

X3 is selected from Gly and Pro;

X4 is selected from Gln and Lys;

X5 is selected from Thr and Ala;

X6 is selected from Asn and Thr; and

X7, if present, is Asn; and

v) Formula IV is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu, Asn, Arg, Ala, Ser, and Lys;

X2 is selected from Gly, Glu, Ala, Val, Thr, and Asp;

X3 is selected from Glu, Thr, Gly, Asp, or Pro;

X4 is selected from Thr, Ile, Gly, Lys, Asp, and Gln;

X5 is selected from Thr, Ser, Val, and Ala;

X6 is selected from Arg, Val, Lys, Pro, Thr, and Asn; and

X7 is selected from Pro, Gly, Phe, Asn, and Arg,

and wherein the AAV variant capsid protein, when present in an AAV virion, provides for increased infectivity of the AAV virion of a retinal cell.

24. The isolated nucleic acid of claim 23, wherein the insertion site is between amino acids 587 and 588 of the AAV2 capsid protein or the corresponding position in the capsid protein of another AAV serotype.

25. The isolated nucleic acid of claim 24, wherein the insertion comprises an amino acid sequence selected from LGETTRP (SEQ ID NO:13), NETITRP (SEQ ID NO:14), KAGQANN (SEQ ID NO:15), KDPKTTN (SEQ ID NO:16), KDTDTTR (SEQ ID NO:57), RAGGSVG (SEQ ID NO:58), AVDTTKF (SEQ ID NO:59), and STGKVPN (SEQ ID NO:60).

26. An isolated, genetically modified host cell comprising the nucleic acid of any one of claims 23-25.

27. A variant adeno-associated virus (AAV) capsid protein, wherein the variant AAV capsid protein comprises a peptide insertion relative to a corresponding parental AAV capsid protein, wherein the insertion site is located between two adjacent amino acids at a position between amino acids 570 and 611 of VP1 of AAV2 or the corresponding position in the capsid protein of another AAV serotype, wherein the insertion is a peptide of Formula I, Formula IIa, Formula IIb, Formula III, or Formula IV, and wherein:

i) Formula I is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu, Asn, and Lys;

X2 is selected from Gly, Glu, Ala, and Asp;

X3 is selected from Glu, Thr, Gly, and Pro;

X4 is selected from Thr, Ile, Gln, and Lys;

X5 is selected from Thr and Ala;

X6 is selected from Arg, Asn, and Thr; and

X7, if present, is selected from Pro and Asn;

ii) Formula IIa is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

each of X1 – X4 is any amino acid;

X5 is Thr;

X6 is Arg; and

X7 is Pro;

iii) Formula IIb is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu and Asn;

X2, if present, is selected from Gly and Glu;

X3 is selected from Glu and Thr;

X4 is selected from Thr and Ile;

X5 is Thr;

X6 is Arg; and

X7 is Pro;

iv) Formula III is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is Lys;

X2 is selected from Ala and Asp;

X3 is selected from Gly and Pro;

X4 is selected from Gln and Lys;

X5 is selected from Thr and Ala;

X6 is selected from Asn and Thr; and

X7, if present, is Asn; and

v) Formula IV is $Y_1Y_2X_1X_2X_3X_4X_5X_6X_7Y_3Y_4$, wherein:

each of Y1 –Y4, if present, is independently selected from Ala, Leu, Gly, Ser, and Thr;

X1, if present, is selected from Leu, Asn, Arg, Ala, Ser, and Lys;

X2 is selected from Gly, Glu, Ala, Val, Thr, and Asp;

X3 is selected from Glu, Thr, Gly, Asp, or Pro;

X4 is selected from Thr, Ile, Gly, Lys, Asp, and Gln;

X5 is selected from Thr, Ser, Val, and Ala;

X6 is selected from Arg, Val, Lys, Pro, Thr, and Asn; and

X7 is selected from Pro, Gly, Phe, Asn, and Arg.

28. The variant AAV capsid protein of claim 27, wherein the insertion comprises an amino acid sequence selected from LGETTRP (SEQ ID NO:13), NETITRP (SEQ ID NO:14), KAGQANN (SEQ ID NO:15), KDPKTTN (SEQ ID NO:16), KDTDTTR (SEQ ID NO:57), RAGGSVG (SEQ ID NO:58), AVDTTKF (SEQ ID NO:59), and STGKVPN (SEQ ID NO:60).

29. The variant AAV capsid protein of claim 27, wherein the insertion site is between amino acids 587 and 588 of the AAV2 capsid protein or the corresponding position in the capsid protein of another AAV serotype.

30. A nucleic acid comprising a nucleotide sequence encoding the variant AAV capsid protein according to any one of claims 27-29.