

STABLE EXPRESSION OF AAV VECTORS IN JUVENILE SUBJECTS

[0001] This application claims priority to the U.S. Provisional Patent Application Serial No. 62/671,271, filed May 14, 2018, which is incorporated by reference herein its entirety.

INCORPORATION BY REFERENCE OF MATERIAL SUBMITTED ELECTRONICALLY

[0002] This application contains, as a separate part of the disclosure, a Sequence Listing in computer-readable form which is incorporated by reference in its entirety and identified as follows: Filename: 53094_Seqlisting.txt; Size: 372,202 bytes, created; May 11, 2019.

FIELD OF INVENTION

[0003] The invention relates to the use of adeno-associated virus (AAV) vectors to achieve long term expression of a transgene in the liver of a juvenile subject. The invention includes the stable long-term amelioration of disease symptoms of the subsection following a single administration of an AAV vector to a juvenile subject, wherein the AAV vector delivers the transgene to the subject's liver.

BACKGROUND

[0004] Adeno-associated virus (AAV) is a small, replication-defective, non-enveloped animal virus that infects humans and some other primate species. Several features of AAV make this virus an attractive vehicle for delivery of therapeutic proteins by gene therapy, including, for example, that AAV is not known to cause human disease and induces a mild immune response, and that AAV vectors can infect both dividing and quiescent cells without integrating into the host cell genome. Gene therapy vectors using AAV have been successfully used in some clinical trials, for example, for the delivery of human Factor IX (FIX) to the liver of adults for the treatment of Hemophilia B.

[0005] Despite their positive features, AAV gene therapy vectors do have some drawbacks. In particular, the cloning capacity of AAV vectors is limited as a consequence of the DNA packaging capacity of the virus. The single-stranded DNA genome of wild-type AAV is about 4.7 kilobases (kb). In practice, AAV genomes of up to about 5.0 kb appear to be completely packaged, i.e., be full-length, into AAV virus particles. With the requirement that the nucleic

acid genome in AAV vectors must have two AAV inverted terminal repeats (ITRs) of about 145 bases, the DNA packaging capacity of an AAV vector is such that a maximum of about 4.4 kb of protein-coding sequence can be encapsidated.

[0006] Another limitation of AAV vectors is that the transgene very rarely integrates into the genome of the targeted cells. Instead, the AAV vector is maintained as an episomal copy. While this lack of genomic integration is desirable in that it reduces the risk of integrated copies disrupting host gene function, the lack of integration is thought to preclude use in dividing cells/growing tissue because the episomal copies are lost over time in dividing cells. This is seen, for example, in juvenile liver where AAV mediated gene delivery resulted in rapid loss of vector genome numbers and concomitant reduction in transgene expression. *See, e.g.,* Cunningham et al., *Molec. Ther.* (2008) vol. 16, pp. 1081-1088.

[0007] There is a need for methods of delivering therapeutic transgenes to the livers of juvenile subjects, where the transgene maintains effective levels of expression of the transgene for clinically significant lengths of time and preferably for the life of the subject. As such, the present invention relates to the use of AAV vectors that encode therapeutic proteins in the liver of juvenile subjects. In particular, the invention provides methods of delivering AAV vectors to the livers of juvenile subjects where only a single administration of AAV vector provides therapeutically effective levels of transgene production for clinically significant lengths of time.

SUMMARY OF INVENTION

[0008] The present invention provides methods of using AAV vectors to express therapeutic proteins in the liver cells of juvenile subjects. The recombinant AAV vectors of the present invention include non-naturally occurring derivatives of the AAV virus into which nucleic acid sequences encoding functional therapeutic proteins have been introduced. The therapeutic proteins replace or compensate for the loss or reduction of an endogenous gene product's activity. Non-limiting examples of therapeutic proteins of the invention include Factor VIII, Factor IX, and phenylalanine hydroxylase (PAH) which are used to replace lost endogenous activity in subjects having hemophilia A, hemophilia B, and phenylketonuria respectively.

[0009] In one aspect, the invention provides a method of ameliorating the symptoms of a genetic disorder in a juvenile subject suffering from the genetic disorder including the step of

administering to the juvenile subject a therapeutically effective amount of a therapeutic AAV virus encoding a therapeutic protein, where the expression of the therapeutic protein ameliorates the symptoms of the genetic disorder.

[0010] In one embodiment of the invention, the therapeutic protein is a functional copy of a non-functional endogenous protein. In another embodiment of the invention the therapeutic protein is a modified version of the endogenous protein. In a further embodiment of the invention the therapeutic protein is a heterologous protein that compensates for a non-functional endogenous protein.

[0011] In an embodiment of the invention, the juvenile subject is a juvenile human. In another embodiment the juvenile human is less than 18 years old. In yet another embodiment of the invention the juvenile human is less than 12 years old.

[0012] In an embodiment of the invention the therapeutic protein is expressed by the hepatocytes of the juvenile subject following administration of the therapeutic AAV virus. In another embodiment of the invention the therapeutic AAV virus is administered intravenously.

[0013] In an embodiment of the invention, the genetic disorder is a hemophilia. In another embodiment of the invention, the genetic disorder is hemophilia A and the therapeutic protein is Factor VIII. In yet another embodiment, the Factor VIII is Factor VIII-SQ. In a preferred embodiment, the therapeutic AAV virus is AAV5-FVIII-SQ. In a further embodiment, the hemophilia is hemophilia B and the therapeutic protein is Factor IX. In another embodiment, the Factor IX is R338L Factor IX.

[0014] In an embodiment of the invention, the genetic disorder is phenylketonuria (PKU) and the therapeutic protein is phenylalanine hydroxylase (PAH).

[0015] In another embodiment of the invention, the amount of therapeutic AAV virus administered to the juvenile subject corresponds to the same absolute number of therapeutic AAV virus that is effective in adult subjects. In yet further embodiments of the invention, from about 1E12 vg/kg to about 1E15 vg/kg of the therapeutic AAV virus are administered to the juvenile subject. In some embodiments, from about 2E12 vg/kg to about 2E13 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 2E12 vg/kg to about 2E14 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from

about 5E12 vg/kg to about 5E13 vg/kg are administered to the juvenile subject or from about 5E13 vg/kg to about 5E14 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or for about 5E13 to about 5E15 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 1E13 vg/kg to about 1E14 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 1E14 vg/kg to about 1E15 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 1E12 vg/kg to about 2E16 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 6E12 vg/kg to about 2E14 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 6E12 vg/kg to about 6E13 vg/kg are administered to the juvenile subject or from about 2E13 vg/kg to about 2E15 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 2E13 vg/kg to about 2E16 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 2E14 vg/kg to about 2E16 vg/kg of the therapeutic AAV virus are administered to the juvenile subject from about 6E13 vg/kg to about 6E14 vg/kg of the therapeutic AAV virus are administered to the juvenile subject.

[0016] In an embodiment of the invention, the AAV virus is formulated as a pharmaceutical composition containing sodium phosphate, dibasic at a concentration of from about 0.1 mg/ml to about 3 mg/ml, sodium phosphate monobasic monohydrate at a concentration of from about 0.1 mg/ml to about 3 mg/ml, sodium chloride at a concentration of from about 1 mg/ml to about 20 mg/ml, mannitol at a concentration of from about 5 mg/ml to about 40 mg/ml, and poloxamer 188 at a concentration of from about 0.1 mg/ml to about 4 mg/ml.

[0017] In certain embodiments of the invention, the juvenile subject is treated prophylactically with a corticosteroid at a concentration ranging from 5 mg/day to 60 mg/day. In other embodiments, the juvenile subject is treated therapeutically with a corticosteroid at a concentration from 5 mg/day to 60 mg/day.

[0018] In an additional embodiment, the invention results in the expression of at least about 5 IU/dl of functional Factor VIII protein in the juvenile subject. Another embodiment results in an increase in functional Factor VIII protein of at least about 1 IU/dl in the juvenile subject.

[0019] In another aspect, the invention provides a method of reducing bleeding time of a bleeding episode in a juvenile subject suffering from hemophilia where the method includes the

step of administering to the juvenile subject, prior to the bleeding episode, a therapeutically effective amount of a therapeutic AAV virus. In an embodiment of the invention, the step of administering occurs at least three weeks prior to the bleeding episode. In another embodiment, the therapeutic AAV virus is administered intravenously. In further embodiments, the hemophilia is hemophilia A and the therapeutic AAV virus expresses Factor VIII. In yet another embodiment, the Factor VIII is Factor VIII-SQ. In a preferred embodiment, the therapeutic AAV virus is AAV5-FVIII-SQ. In another embodiment, the hemophilia is hemophilia B and the therapeutic AAV virus expresses Factor IX. In yet another embodiment, the Factor IX is R338L Factor IX. In yet another embodiment, the amount of therapeutic AAV virus administered to the juvenile subject corresponds to the same absolute number of therapeutic AAV virus that is effective in adult subjects. In further embodiments, from about 1E12 vg/kg to about 1E15 vg/kg of the therapeutic AAV virus are administered to the juvenile subject. In additional exemplary embodiments, from about 1E12 vg/kg to about 1E16 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 2E12 vg/kg to about 2E13 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 2E12 vg/kg to about 2E14 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 5E13 vg/kg to about 5E14 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 6E12 vg/kg to about 6E14 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 6E13 vg/kg to about 6E14 vg/kg of the therapeutic AAV virus are administered to the juvenile subject. In an embodiment, the therapeutic AAV virus is formulated in a solution comprising sodium phosphate, dibasic at a concentration of from about 0.1 mg/ml to about 3 mg/ml, sodium phosphate monobasic monohydrate at a concentration of from about 0.1 mg/ml to about 3 mg/ml, sodium chloride at a concentration of from about 1 mg/ml to about 20 mg/ml, mannitol at a concentration of from about 5 mg/ml to about 40 mg/ml, and poloxamer 188 at a concentration of from about 0.1 mg/ml to about 4 mg/ml.

[0020] In another aspect, the invention provides a method of increasing Factor VIII protein expression in a juvenile subject in need thereof where the method includes the step of administering to the juvenile subject a therapeutic virus, wherein the therapeutic AAV virus is AAV5-FVIII-SQ. In an embodiment of the invention, the therapeutic AAV virus is administered intravenously. In yet another embodiment, the amount of therapeutic AAV virus administered to

the juvenile subject corresponds to the same absolute number of therapeutic AAV virus that is effective in adult subjects. In another embodiment, from about $1\text{E}12$ vg/kg to about $1\text{E}15$ vg/kg of the therapeutic AAV virus are administered to the juvenile subject. In a further embodiment, from about $6\text{E}13$ vg/kg to about $6\text{E}14$ vg/kg of the therapeutic AAV virus are administered to the juvenile subject. In other embodiments, the invention results in expression of at least about 5 IU/dl of functional Factor VIII protein in the juvenile subject. In additional embodiments the invention results in expression of at least about 1 IU/dl of functional Factor VIII protein in the juvenile subject. In yet another embodiment, the invention results in an increase in functional FVIII activity of at least about 1 IU/dl in the juvenile subject. In an embodiment, the juvenile subject is treated with a corticosteroid at a concentration ranging from 5 mg/day to 60 mg/day. In other embodiments, the corticosteroid treatment is performed prophylactically. In further embodiments, the corticosteroid treatment is performed therapeutically. In a further embodiment, the juvenile subject is treated with a corticosteroid at a concentration ranging from 5 mg/day to 60 mg/day over a continuous period of at least 3, 4, 5, 6, 7, 8, 9, or 10 weeks or greater. An embodiment of the invention includes the step of determining the absence or presence of anti-AAV capsid antibodies in the serum of the juvenile subject after administration of the therapeutically effective amount of the AAV5-FVIII-SQ. In another embodiment, the invention includes the step of administering an effective amount of a corticosteroid to the subject after a determination of the presence of anti-AAV capsid antibodies in the serum of the juvenile subject is made.

[0021] The genomes encoding functionally active therapeutic proteins are preferably at most 7.0 kb in length, more preferably at most 6.5 kb in length, yet more preferably at most 6.0 kb in length, yet more preferably at most 5.5 kb in length, yet more preferably at most 5.0 kb in length, with enhanced promoter function.

[0022] As used herein, a "functionally active Factor VIII" or "functionally active FVIII" is a FVIII protein that has the functionality of a wild-type FVIII protein in vitro, when expressed in cultured cells, or in vivo, when expressed in cells or body tissues. Throughout this application the terms "Factor VIII" and "FVIII" are identical and are used interchangeably. This includes, for example, functionally contributing in the blood coagulation cascade and/or reducing the time that it takes for blood to clot in a subject suffering from hemophilia A. Wild-type FVIII participates in blood coagulation via the coagulation cascade, acting as a co-factor for activated

Factor IX (FIXa) which, in the presence of calcium ions and phospholipids forms a complex that converts Factor X (FX) into activated FX (FXa). Accordingly, a functionally active FVIII can form a complex with FIXa, which can convert FX to FXa. One example of a functionally active FVIII protein is a FVIII SQ protein as described in WO 2015/038625, herein incorporated by reference.

[0023] The invention also provides for methods of increasing PAH protein expression in a juvenile subject in need thereof comprising administering to the juvenile subject a therapeutic virus, wherein the therapeutic AAV virus is AAV5-PAH. For example, in any of the methods, the therapeutic AAV virus is administered intravenously. The invention also provides for use of a therapeutic AAV virus for the preparation of a medicament for increasing PAH protein expression in a juvenile subject in need thereof, wherein the AAV virus is AAV5-PAH. In another embodiment, the invention provides for compositions comprising a therapeutic AAV virus for increasing PAH protein expression in a juvenile subject in need thereof, wherein the AAV virus is AAV5-PAH. In any of the uses or compositions, the AAV virus is formulated for intravenous administration. In these methods, uses and compositions for increasing expression of PAH, from about 1E12 vg/kg to about 1E16 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 2E12 vg/kg to about 2E13 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 2E12 vg/kg to about 2E14 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 5E13 vg/kg to about 5E14 vg/kg of the therapeutic AAV virus are administered to the juvenile subject or from about 6E12 vg/kg to about 6E14 vg/kg of the therapeutic AAV virus are administered to the juvenile subject. In any of the methods, uses and compositions, the juvenile subject is about 3 weeks to about 5 weeks of age. For example the juvenile subject is about 3 weeks of age, or about 4 weeks of age, or about 5 weeks of age, or about 22 days of age, or about 23 days of age, or about 24 days of age, or about 25 days of age, or about 26 days of age, or about 27 days of age, or about 29 days of age, or about 30 days of age, or about 31 days of age, or about 32 days of age, or about 33 days of age, or about 34 days of age. In addition, any of these methods can further comprise a step of determining the absence or presence of anti-AAV capsid antibodies in the serum of the juvenile subject after administration of the therapeutically effective amount of the AAV5-PAH.

[0024] As used herein, an "AAV vector" refers to nucleic acids, either single-stranded or double-stranded, having an AAV 5' inverted terminal repeat (ITR) sequence and an AAV 3' ITR flanking a protein-coding sequence (preferably a functional therapeutic protein-encoding sequence; e.g., FVIII, FIX, and PAH) operably linked to transcription regulatory elements that are heterologous to the AAV viral genome, i.e., one or more promoters and/or enhancers and, optionally, a polyadenylation sequence and/or one or more introns inserted between exons of the protein-coding sequence. A single-stranded AAV vector refers to nucleic acids that are present in the genome of an AAV virus particle, and can be either the sense strand or the anti-sense strand of the nucleic acid sequences disclosed herein. The size of such single-stranded nucleic acids is provided in bases. A double-stranded AAV vector refers to nucleic acids that are present in the DNA of plasmids, e.g., pUC19, or genome of a double-stranded virus, e.g., baculovirus, used to express or transfer the AAV vector nucleic acids. The size of such double-stranded nucleic acids is provided in base pairs (bp).

[0025] The term "inverted terminal repeat (ITR)" as used herein refers to the art-recognized regions found at the 5' and 3' termini of the AAV genome which function in cis as origins of DNA replication and as packaging signals for the viral genome. AAV ITRs, together with the AAV rep coding region, provide for efficient excision and rescue from, and integration of a nucleotide sequence interposed between two flanking ITRs into a host cell genome. Sequences of certain AAV-associated ITRs are disclosed by Yan et al., *J. Virol.* (2005) vol. 79, pp. 364-379 which is herein incorporated by reference in its entirety. ITR sequences that find use herein may be full length, wild-type AAV ITRs or fragments thereof that retain functional capability, or may be sequence variants of full-length, wild-type AAV ITRs that are capable of functioning in cis as origins of replication. AAV ITRs useful in the recombinant AAV FVIII vectors of the present invention may be derived from any known AAV serotype and, in certain preferred embodiments, derived from the AAV2 or AAV5 serotype.

[0026] A "transcription regulatory element" refers to nucleotide sequences of a gene involved in regulation of genetic transcription including a promoter, plus response elements, activator and enhancer sequences for binding of transcription factors to aid RNA polymerase binding and promote expression, and operator or silencer sequences to which repressor proteins bind to block RNA polymerase attachment and prevent expression. The term "liver specific transcription regulatory element" refers to a regulatory element that modulates gene expression specifically in

the liver tissue. Examples of liver specific regulatory elements include, but are not limited to, the mouse thyretin promoter (mTTR), the endogenous human factor VIII promoter (F8), human alpha-1-antitrypsin promoter (hAAT) and active fragments thereof, human albumin minimal promoter, and mouse albumin promoter. Enhancers derived from liver specific transcription factor binding sites are also contemplated, such as EBP, DBP, HNF1, HNF3, HNF4, HNF6, with Enh1.

[0027] In one embodiment, the AAV vector of the invention comprises a nucleic acid encoding functionally active Factor VIII protein having the B domain replaced by the 14 amino acid SQ sequence. The SQ sequence is disclosed in Ward et al., *Blood* (2011) vo. 117, pp. 798-807; McIntosh et al., *Blood* (2013) vo. 121, pp. 3335-3344; WO 2013/186563; and WO 2015/038625. The FVIII coding region sequence may be a codon-optimized FVIII-encoding sequence (*see, e.g.*, U.S. Patent Application Publications US2015158930, US2015071883, and US20170216408; and U.S. Patents 9,447,168 and 9,504,762 which are all incorporated herein by reference in their entireties). In an exemplary embodiment, the nucleic acid encoding the functionally active human FVIII protein of the AAV vector or recombinant AAV virus particle consists of nucleotides 403 to 4776 of the nucleic acid sequence of SEQ ID NO:1 which encodes a functional FVIII protein sequence; this sequence is herein referred to as "FVIII-SQ" or "Factor VIII-SQ." In exemplary embodiments, the AAV vector of the invention comprises the nucleic acid sequence set forth in any one of SEQ ID NOS: 1-45.

[0028] In an embodiment, the AAV vector of the invention comprises a nucleic acid encoding a functionally active Factor IX protein. The Factor IX coding sequence may be wild-type, codon optimized, or a variant (*see, e.g.*, U.S. Patent 4,994,371 which is incorporated by reference herein in its entirety). In certain embodiments, the Factor IX coding sequence encodes a protein with a change in the arginine residue at position 338, where the arginine residue is changed to an alanine, valine, leucine, isoleucine phenylalanine, tryptophan, methionine, serine, or threonine. In a preferred embodiment the arginine residue at position 338 is changed into a leucine (R338L Factor IX) (*see, e.g.*, U.S. Patent 6,531, 298; U.S. Patent 9,249,405; U.S. Patent Application Publication US2002/0031799; and U.S. Patent Application Publication US2011/0244550 all of which are incorporated by reference in their entireties). In an exemplary embodiment, the AAV vector of the invention comprises the nucleic acid sequence encoding the Factor IX protein

sequence of SEQ ID NO: 46 or a modified FIX protein which has a change in the arginine at position 338 of SEQ ID NO: 46.

[0029] In a further embodiment, the AAV vector of the invention comprises a nucleic acid encoding a functionally active phenylalanine hydroxylase (PAH) protein, such as a nucleic acid sequence encoding the wild-type PAH amino acid sequence of SEQ ID NO: 48. The PAH encoding sequence may be wild-type, codon optimized, or a variant (see e.g., Fang et al., *Gene Ther.*, vol. 1, pages 247-254 (1994); Eisensmith et al., *J. Inherit. Metab. Dis.*, vol. 19, pages 412-423 (1996); Nagasaki et al., *Pediatr. Res.*, vol. 45, pages 465-473 (1999); and Laipis et al., *Mol. Ther.*, vol. 7, pages S391-S392 (2003)). The wild-type PAH is encoded by the nucleic acid sequence of SEQ ID NO: 47. In an exemplary embodiment, the AAV vector of the invention comprises the nucleic acid sequence encoding the wild-type PAH protein sequence of SEQ ID NO: 48. In exemplary embodiments, the AAV vector of the invention comprises the nucleic acid sequence set forth in any one of SEQ ID NO: 49- 55. Exemplary AAV vectors comprising a nucleic acid encoding a functionally active PAH are provided in U.S. Provisional Application No. 62/755,207 and the International Application No. PCT/US2019/031252 filed May 8, 2019 (which claims priority to U.S. Provisional Application No. 62/755,207), both of which are incorporated by reference herein in their entirety.

[0030] In other embodiments, the recombinant AAV vector of the invention comprises a nucleic acid comprising an AAV2 5' inverted terminal repeat (ITR) (which may or may not be modified as known in the art), a liver-specific *transcription* regulatory region, a codon-optimized therapeutic protein coding region, optionally one or more introns, a polyadenylation sequence, and an AAV2 3' ITR (which may or may not be modified as known in the art). In certain embodiments the therapeutic protein is human Factor VIII or variants thereof. In other embodiments, the therapeutic protein is human Factor IX or variants thereof. In additional embodiments the therapeutic protein is human PAH or variants thereof. In a preferred embodiment, the liver-specific transcription regulatory region comprises a shortened ApoE enhancer sequence; a 186 base human alpha anti-trypsin (hAAT) proximal promoter, including 42 bases of the 5' untranslated region (UTR); one or more enhancers selected from the group consisting of (i) a 34 base human ApoE/C1 enhancer, (ii) a 32 base human AAT promoter distal X region, and (iii) 80 additional bases of distal element of the human AAT proximal promoter; and a codon-optimized functionally active FVIII coding region encoding the FVIII-SQ variant.

In another preferred embodiment, the liver specific transcription regulatory region comprises an α -microglobulin enhancer sequence and the 186 base human alpha anti-trypsin (AAT) proximal promoter.

[0031] In yet other embodiments, the present invention is directed to vector constructs encoding a functional Factor VIII polypeptide, wherein the constructs comprise one or more of the individual elements of the above described constructs and combinations thereof, in one or more different orientation(s). The present invention is also directed to the above described constructs in an opposite orientation. The present invention is also directed to recombinant AAV virus particles comprising the herein described AAV FVIII vectors and their use for the treatment of hemophilia A.

[0032] In further embodiments, the present invention is directed to vector constructs encoding a functional Factor IX polypeptide, wherein the constructs comprise one or more of the individual elements of the above described constructs and combinations thereof, in one or more different orientation(s). The present invention is also directed to the above described constructs in an opposite orientation. The present invention is also directed to recombinant AAV virus particles comprising the herein described AAV IX vectors and their use for the treatment of hemophilia B in juvenile subjects.

[0033] In yet other embodiments, the present invention is directed to vector constructs encoding a functional PAH polypeptide, wherein the constructs comprise one or more of the individual elements of the above described constructs and combinations thereof, in one or more different orientation(s). The present invention is also directed to the above described constructs in an opposite orientation. The present invention is also directed to recombinant AAV virus particles comprising the herein described AAV PAH vectors and their use for the treatment of PKU in juvenile subjects.

[0034] The AAV vectors of the invention in single strand form are less than about 7.0 kb in length, or is less than 6.5 kb in length, or is less than 6.4 kb in length, or is less than 6.3 kb in length, or is less than 6.2 kb in length, or is less than 6.0 kb in length, or is less than 5.8 kb in length, or is less than 5.6 kb in length, or is less than 5.5 kb in length, or is less than 5.4 kb in length, or is less than 5.4 kb in length, or is less than 5.2 kb in length or is less than 5.0 kb in length. The AAV vectors of the invention in single strand form range from about 5.0 kb to about

6.5 kb in length, or ranges from about 4.8 kb to about 5.2 k in length, or 4.8 kb to 5.3 kb in length, or ranges from about 4.9 kb to about 5.5 kb in length, or about 4.8 kb to about 6.0 kb in length, or about 5.0 kb to 6.2 kb in length or about 5.1 kb to about 6.3 kb in length, or about 5.2 kb to about 6.4 kb in length, or about 5.5 kb to about 6.5 kb in length.

[0035] In another embodiment, the invention provides for methods of producing a recombinant adeno-associated virus (AAV) particles comprising any of the AAV vectors of the invention. The methods comprise the steps of culturing a cell that has been transfected with any of the AAV vectors of the invention (in association with various AAV cap and rep genes) and recovering recombinant therapeutic AAV virus particles from the supernatant of the transfected cell.

[0036] The cells of the invention useful for recombinant AAV production are any cell type susceptible to baculovirus infection, including insect cells such as High Five, Sf9, Se301, SeIZD2109, SeUCR1, Sf9, Sf900+, Sf21, BTI-TN-5B1-4, MG-1, Tn368, HzAm1, BM-N, Ha2302, Hz2E5, and Ao38. Preferred mammalian cells used can be HEK293, HeLa, CHO, NSO, SP2/0, PER.C6, Vero, RD, BHK, HT 1080, A549, Cos-7, ARPE-19, and MRC-5.

[0037] The invention also provides for a recombinant viral particle comprising any of the AAV vectors of the invention or any viral particle produced by the forgoing methods of the invention.

[0038] An "AAV virion" or "AAV viral particle" or "AAV vector particle" or "AAV virus" refers to a viral particle composed of at least one AAV capsid protein and an encapsidated polynucleotide AAV vector as described herein. 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 "AAV vector particle" or simply an "AAV vector". Thus, production of AAV vector particles necessarily includes production of AAV vector, as such a vector is contained within an AAV vector particle.

[0039] As used herein "therapeutic AAV virus" refers to an AAV virion, AAV viral particle, AAV vector particle, or AAV virus that comprises a heterologous polynucleotide that encodes a therapeutic protein.

[0040] As used herein “therapeutic protein” refers to a polypeptide that has a biological activity that replaces or compensates for the loss or reduction of activity of an endogenous protein. For example, a functional copy of human Factor VIII, or a functional fragment thereof, is a therapeutic protein when used to replace the activity of the inactive human Factor VIII in subjects having hemophilia A. Similarly, functional human Factor IX is a therapeutic protein for subjects with hemophilia B, and functional phenylalanine hydroxylase (PAH) is a therapeutic protein for phenylketonuria (PKU).

[0041] As used herein “juvenile subject” refers to a subject that is physiologically immature or undeveloped. In particular, a juvenile subject is one in which the cells of multiple tissues or organs are still dividing at a rate greater than that of a mature subject. In certain embodiments, the juvenile subject is a human. In another embodiment, the juvenile subject is a human under eighteen years of age. In yet another embodiment, the juvenile subject is a human under twelve years of age. Juvenile subjects of the invention include humans that are less than 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, or 18 years of age.

[0042] As used herein “genetic disorder” refers to a disorder caused by one or more abnormalities in the genome of a subject. In a preferred embodiment, the genetic disorder is monogenic meaning that it results from an abnormality in one or both copies of a single gene. The genomic abnormality disrupts a gene and leads to a reduction or loss of activity of the endogenous protein encoded by the disrupted gene, and the symptoms of the genetic disorder result from the reduction or loss of activity of the endogenous protein.

[0043] As used herein “stably treating” or “stable treatment” refers to a therapeutic treatment using a therapeutic AAV virus administered to a juvenile subject where the juvenile subject stably expresses a therapeutic protein expressed by the therapeutic AAV virus. Stably expressed therapeutic protein means that the protein is expressed for a clinically significant length of time. “Clinically significant length of time” as used herein means expression at therapeutically effective levels for a length of time that has a meaningful impact on the quality of life of the juvenile subject. In certain embodiments a meaningful impact on the quality of life is demonstrated by the lack of a need to administer alternative therapies intravenously or subcutaneously. In certain embodiments clinically significant length of time is expression for at least six months, for at least eight months, for at least one year, for at least two years, for at least

three years, for at least four years, for at least five years, for at least six years, for at least seven years, for at least eight years, for at least nine years, for at least ten years, or for at least the life of the subject.

[0044] In another embodiment, the invention provides for methods of treating a juvenile subject suffering from hemophilia A comprising administering to the juvenile subject a therapeutically effective amount of any of the Factor VIII AAV vectors of the invention, or a viral particle of the invention or a viral particle produced by a method of the invention.

[0045] In another embodiment, the invention provides for methods of increasing circulating FVIII protein levels in a juvenile subject in need thereof comprising administering to the juvenile subject any of the AAV vectors of the invention, or a viral particle of the invention or a viral particle produced by a method of the invention.

[0046] In another embodiment, the invention provides for methods of increasing circulating Factor IX protein levels in a juvenile subject in need thereof comprising administering to the juvenile subject any of the AAV vectors of the invention, or a viral particle of the invention or a viral particle produced by a method of the invention.

[0047] In another embodiment, the invention provides for methods for increasing circulating PAH protein levels in a subject in need thereof comprising administering to the subject any of the AAV vectors of the invention, or viral particles of the invention or a viral particle produced by a method of the invention that express the PAH protein.

[0048] In another embodiment, the invention provides for pharmaceutical formulations comprising therapeutic AAV virus particles as described herein. More specifically, in certain aspects, the present invention is directed to pharmaceutical formulations that comprise a recombinant AAV virus expressing Factor VIII, Factor IX, or PAH; a buffering agent; an isotonicity agent; a bulking agent; and a surfactant. In particularly preferred embodiments, the pharmaceutical formulations of the present invention comprise AAV5-FVIII-SQ or any of the other herein described vectors and/or are stable during storage for at least two weeks.

[0049] In yet other embodiments of the present invention, the pharmaceutical formulation comprises sodium phosphate, dibasic at a concentration of from about 0.1 mg/ml to about 3 mg/ml, sodium phosphate monobasic monohydrate at a concentration of from about 0.1 mg/ml to

about 3 mg/ml, sodium chloride at a concentration of from about 1 mg/ml to about 20 mg/ml, mannitol at a concentration of from about 5 mg/ml to about 40 mg/ml, and poloxamer 188 at a concentration of from about 0.1 mg/ml to about 4 mg/ml. In a particularly preferred embodiment, the pharmaceutical formulation of the present invention comprises sodium phosphate, dibasic at a concentration of about 1.42 mg/ml, sodium phosphate monobasic monohydrate at a concentration of about 1.38 mg/ml, sodium chloride at a concentration of about 8.18 mg/ml, mannitol at a concentration of about 20 mg/ml, and poloxamer 188 at a concentration of about 2 mg/ml.

[0050] The pharmaceutical formulations of the present invention may be in liquid form and may comprise the AAV therapeutic protein virus particle at a concentration of from about 1E12 vg/ml to about 2E14 vg/ml, more preferably at a concentration of about 2E13 vg/ml. In one embodiment, the pharmaceutical formulations of the invention are useful for intravenous administration to a human suffering from hemophilia A, hemophilia B, or PKU.

[0051] The present invention is also directed to methods, uses and compositions for stably treating a juvenile subject suffering from hemophilia A which includes the step of administering to the subject a therapeutically effective amount of a recombinant AAV Factor VIII virus, which optionally may be formulated as described above. In a preferred embodiment, the juvenile subject suffering from hemophilia A is a human. In one embodiment, the recombinant AAV Factor VIII virus is AAV5-FVIII-SQ. In one embodiment, the step of administering is accomplished by intravenous (IV) administration. In certain aspects of the present invention, the step of administration results in stable expression of at least about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, or more IU/dl of Factor VIII protein in the bloodstream of the juvenile subject, preferably at least about 5 IU/dl of Factor VIII protein in the bloodstream of the juvenile subject. In certain embodiments, the step of administration results in expression of at least about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, or more IU/dl of Factor VIII protein in the bloodstream of the juvenile subject 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, or more weeks after administration. In certain embodiments, the Factor VIII protein is expressed for at least about 6, 7, 8, 9, 10, 11, 12, or more months in the bloodstream of the juvenile subject. In certain embodiments the Factor VIII protein is expressed for at least about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, or more years in the bloodstream of the juvenile subject. In certain embodiments, the therapeutically effective amount of AAV Factor VIII virus administered to the juvenile subject is based on the same

absolute number of therapeutic AAV virus found to be an effective dose in an adult subject. The therapeutically effective amount can range from at least 1E12 vg/kg of body weight to at least 1E15 vg/kg of body weight.

[0052] In certain embodiments, in addition to administration of a therapeutically effective amount of AAV Factor VIII virus, the subject is treated either prophylactically, therapeutically, or both with a corticosteroid to prevent and/or treat any hepatotoxicity associated with administration of the AAV Factor VIII virus. In one embodiment, associated hepatotoxicity is measured by comparing baseline (i.e., pre-dosing with Factor VIII AAV) alanine transaminase (ALT) levels to post-treatment ALT levels, wherein an increase in ALT levels post-dosing is evidence of associated hepatotoxicity. Prophylactic corticosteroid treatment refers to the administration of a corticosteroid to prevent hepatotoxicity and/or to prevent an increase in measured ALT levels in the subject. Therapeutic corticosteroid treatment refers to the administration of a corticosteroid to reduce hepatotoxicity caused by administration of an AAV Factor VIII virus and/or to reduce an elevated ALT concentration in the bloodstream of the subject caused by administration of an AAV Factor VIII virus. In certain embodiments, prophylactic or therapeutic corticosteroid treatment may comprise administration of at least 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, or more mg/day of the corticosteroid to the subject. In certain embodiments, prophylactic or therapeutic corticosteroid treatment of a subject may occur over a continuous period of at least about 3, 4, 5, 6, 7, 8, 9, 10 weeks, or more.

[0053] The present invention is also directed to methods, uses and compositions for stably treating a juvenile subject suffering from hemophilia B which comprise the step of administering to the subject a therapeutically effective amount of a recombinant AAV Factor IX virus, which optionally may be formulated as described above. In a preferred embodiment, the juvenile subject suffering from hemophilia B is a human. In one embodiment, the recombinant AAV Factor IX virus expresses R338L Factor IX. In one embodiment, the step of administering is accomplished by intravenous (IV) administration. In certain aspects of the present invention, the step of administration results in stable expression of at least about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, or more IU/dl of Factor IX protein in the bloodstream of the juvenile subject, preferably at least about 5 IU/dl of Factor IX protein in the bloodstream of the juvenile subject. In certain embodiments, the step of administration results in expression of at least about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, or more IU/dl of Factor IX protein in the bloodstream of the juvenile subject 1, 2, 3, 4,

5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, or more weeks after administration. In certain embodiments, the Factor IX protein is expressed for at least about 6, 7, 8, 9, 10, 11, 12, or more months in the bloodstream of the juvenile subject. In certain embodiments the Factor IX protein is expressed for at least about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 or more years in the bloodstream of the juvenile subject. In certain embodiments, the therapeutically effective amount of AAV Factor IX virus administered to the juvenile subject is based on the same absolute number of therapeutic AAV virus found to be an effective dose in an adult subject. The therapeutically effective amount can range from at least 1E12 vg/kg of body weight to at least 1E15 vg/kg of body weight. In certain embodiments, in addition to administration of a therapeutically effective amount of AAV Factor IX virus, the subject is treated either prophylactically, therapeutically, or both with a corticosteroid to prevent and/or treat any hepatotoxicity associated with administration of the AAV Factor IX virus. In one embodiment, associated hepatotoxicity is measured by comparing baseline (i.e., pre-dosing with Factor IX AAV) alanine transaminase (ALT) levels to post-treatment ALT levels, wherein an increase in ALT levels post-dosing is evidence of associated hepatotoxicity. Prophylactic corticosteroid treatment refers to the administration of a corticosteroid to prevent hepatotoxicity and/or to prevent an increase in measured ALT levels in the subject. Therapeutic corticosteroid treatment refers to the administration of a corticosteroid to reduce hepatotoxicity caused by administration of an AAV Factor IX virus and/or to reduce an elevated ALT concentration in the bloodstream of the subject caused by administration of an AAV Factor IX virus. In certain embodiments, prophylactic or therapeutic corticosteroid treatment may comprise administration of at least 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, or more mg/day of the corticosteroid to the subject. In certain embodiments, prophylactic or therapeutic corticosteroid treatment of a subject may occur over a continuous period of at least about 3, 4, 5, 6, 7, 8, 9, 10 weeks, or more.

[0054] The present invention is also directed to use of a therapeutically effective amount of recombinant AAV Factor VIII virus for the preparation of a medicament for the treatment of a juvenile subject suffering from hemophilia A. In certain embodiments, the AAV Factor VIII virus is AAV5-FVIII-SQ or a virus comprising the p-100 ATGB vector. The medicament optionally may be formulated as described above. In a preferred embodiment, the juvenile subject suffering from hemophilia A is a human. In one embodiment, the medicament is administered by intravenous (IV) administration. In one aspect of the present invention,

administration of the medicament results in expression of at least about 5 IU/dl of Factor VIII protein in the bloodstream of the subject, preferably at least about 5 IU/dl of Factor VIII protein in the bloodstream of the juvenile subject 16 weeks or more after administration. In certain embodiments, the medicament also comprises a prophylactic and/or therapeutic corticosteroid for the prevention and/or treatment of any hepatotoxicity associated with administration of the AAV Factor VIII virus. The medicament comprising a prophylactic or therapeutic corticosteroid treatment may comprise at least 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, or more mg/day of the corticosteroid. In certain embodiments, the medicament comprising a prophylactic or therapeutic corticosteroid may be administered over a continuous period of at least about 3, 4, 5, 6, 7, 8, 9, 10 weeks, or more.

[0055] The present invention is also directed to use of a therapeutically effective amount of recombinant AAV Factor IX virus for the preparation of a medicament for the treatment of a juvenile subject suffering from hemophilia B. In certain embodiments, the AAV Factor IX virus expresses R338L Factor IX. The medicament optionally may be formulated as described above. In a preferred embodiment, the juvenile subject suffering from hemophilia B is a human. In one embodiment, the medicament is administered by intravenous (IV) administration. In one aspect of the present invention, administration of the medicament results in expression of at least about 5 IU/dl of Factor IX protein in the bloodstream of the subject, preferably at least about 5 IU/dl of Factor IX protein in the bloodstream of the juvenile subject 16 weeks or more after administration. In certain embodiments, the medicament also comprises a prophylactic and/or therapeutic corticosteroid for the prevention and/or treatment of any hepatotoxicity associated with administration of the AAV Factor IX virus. The medicament comprising a prophylactic or therapeutic corticosteroid treatment may comprise at least 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, or more mg/day of the corticosteroid. In certain embodiments, the medicament comprising a prophylactic or therapeutic corticosteroid may be administered over a continuous period of at least about 3, 4, 5, 6, 7, 8, 9, 10 weeks, or more.

[0056] The present invention is also directed to a composition comprising a therapeutically effective amount of a recombinant AAV Factor VIII virus for use in reducing bleeding time of a bleeding episode in a juvenile subject suffering from hemophilia A. In one embodiment, the AAV Factor VIII virus is AAV5-FVIII-SQ. The composition optionally may be formulated as described above. In a preferred embodiment, the juvenile subject suffering from hemophilia A is

a human. The composition may be administered prior to the bleeding episode. In one embodiment, the composition is administered by intravenous (IV) administration prior to the bleeding episode. In one aspect of the present invention, the step of administration results in expression of at least about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, or more IU/dl of Factor VIII protein in the bloodstream of the juvenile subject, preferably at least about 5 IU/dl of Factor VIII protein in the bloodstream of the juvenile subject. In certain embodiments, the step of administration results in expression of at least about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, or more IU/dl of Factor VIII protein in the bloodstream of the juvenile subject 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, or more weeks after administration. In certain embodiments, compositions comprising a therapeutically effective amount of AAV Factor VIII virus for use in reducing bleeding time are administered with a composition comprising a prophylactic and/or therapeutic corticosteroid for use in preventing and/or treating any hepatotoxicity associated with administration of the AAV Factor VIII virus, as described above.

[0057] The present invention is also directed to a composition comprising a therapeutically effective amount of a recombinant AAV Factor IX virus for use in reducing bleeding time of a bleeding episode in a juvenile subject suffering from hemophilia A. In one embodiment, the AAV Factor IX expresses R338L Factor IX. The composition optionally may be formulated as described above. In a preferred embodiment, the juvenile subject suffering from hemophilia A is a human. The composition may be administered prior to the bleeding episode. In one embodiment, the composition is administered by intravenous (IV) administration prior to the bleeding episode. In one aspect of the present invention, the step of administration results in expression of at least about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, or more IU/dl of Factor IX protein in the bloodstream of the juvenile subject, preferably at least about 5 IU/dl of Factor IX protein in the bloodstream of the juvenile subject. In certain embodiments, the step of administration results in expression of at least about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, or more IU/dl of Factor IX protein in the bloodstream of the juvenile subject 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, or more weeks after administration. In certain embodiments, compositions comprising a therapeutically effective amount of AAV Factor IX virus for use in reducing bleeding time are administered with a composition comprising a prophylactic and/or therapeutic corticosteroid for use in preventing and/or treating any hepatotoxicity associated with administration of the AAV Factor IX virus, as described above.

[0058] The present invention is also directed to use of a therapeutically effective amount of recombinant AAV PAH virus for the preparation of a medicament for the treatment of a juvenile subject suffering from PKU. The medicament optionally may be formulated as described above. In a preferred embodiment, the juvenile subject suffering from PKU is a human. In one embodiment, the medicament is administered by intravenous (IV) administration. In one aspect of the present invention, administration of the medicament results in expression of PAH protein in the bloodstream of the subject sufficient to lower the concentration of phenylalanine in the bloodstream of the juvenile subject 16 weeks or more after administration. In certain embodiments, the medicament also comprises a prophylactic and/or therapeutic corticosteroid for the prevention and/or treatment of any hepatotoxicity associated with administration of the AAV PAH virus. The medicament comprising a prophylactic or therapeutic corticosteroid treatment may comprise at least 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, or more mg/day of the corticosteroid. In certain embodiments, the medicament comprising a prophylactic or therapeutic corticosteroid may be administered over a continuous period of at least about 3, 4, 5, 6, 7, 8, 9, 10 weeks, or more.

[0059] The present invention is also directed to methods for inducing expression of a functional therapeutic protein in a juvenile subject in need thereof which comprise the step of administering to the subject a recombinant AAV virus that expresses a therapeutic protein as described herein, which optionally may be formulated as described herein, wherein such administration results in increased expression of functional therapeutic protein or increased concentrations of functional therapeutic protein in the bloodstream of the subject. In a preferred embodiment, the subject in need is a human. In one embodiment, the step of administering is accomplished by intravenous (IV) administration. In one aspect of the present invention, the step of administration results in expression of the therapeutic protein in the bloodstream of the juvenile subject, preferably to at least about 5%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%, 110%, 120%, 130%, 140%, or 150% of the level of the therapeutic protein found in a normal juvenile subject. In certain embodiments, the step of administration results in expression of at least about at least about 5%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%, 110%, 120%, 130%, 140%, or 150% of the level of the therapeutic protein found in a normal juvenile subject in the bloodstream of the juvenile subject

1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, or more weeks after administration.

[0060] In certain embodiments, in addition to administration of an AAV virus expressing a therapeutic protein, the subject is treated either prophylactically, therapeutically, or both with a corticosteroid to prevent and/or treat any hepatotoxicity associated with administration of the AAV virus, as described above. In addition, in any of the methods of the invention after administration of the AAV virus to increase expression of the therapeutic protein, the absence or presence of anti-AAV capsid antibodies in the serum of the subject is determined. If the subject is determined to have anti-AAV capsid antibodies in the serum, administration of an effective amount of a corticosteroid to the subject having anti-AAV capsid antibodies in the serum is contemplated.

[0061] The present invention is also directed to use of the AAV virus of the invention for the preparation of a medicament for inducing expression of a functional therapeutic protein in a juvenile subject in need thereof, wherein the recombinant AAV virus expresses a therapeutic protein as described herein, and the medicament optionally may be formulated as described herein, wherein such medicament results in increased expression of functional therapeutic protein or increased concentrations of functional therapeutic protein in the bloodstream of the subject. In a preferred embodiment, the medicament is administered to a human subject in need. In one embodiment, the medicament is administered by intravenous (IV) administration. In one aspect of the present invention, the administration of the medicament results in expression of the therapeutic protein in the bloodstream of the juvenile subject, preferably to at least about 5%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%, 110%, 120%, 130%, 140%, or 150% of the level of the therapeutic protein found in a normal juvenile subject. In certain embodiments, the administration of the medicament results in expression of at least about 5%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%, 110%, 120%, 130%, 140%, or 150% of the level of the therapeutic protein found in a normal juvenile subject in the bloodstream of the juvenile subject 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, or more weeks after administration.

[0062] In certain embodiments, in addition to administration of an AAV virus expressing a therapeutic protein, the subject is treated either prophylactically, therapeutically, or both with a

corticosteroid to prevent and/or treat any hepatotoxicity associated with administration of the AAV virus, as described above. In addition, in any of the uses of the invention after administration of the medicament to increase expression of the therapeutic protein, the absence or presence of anti-AAV capsid antibodies in the serum of the subject is determined. If the subject is determined to have anti-AAV capsid antibodies in the serum, use of an effective amount of a corticosteroid for the preparation of a medicament for the administration to the subject having anti-AAV capsid antibodies in the serum is contemplated.

[0063] The present invention is also directed to compositions for inducing expression of a functional therapeutic protein in a juvenile subject in need thereof wherein the composition comprises a recombinant AAV virus that expresses a therapeutic protein as described herein, which optionally may be formulated as described herein, wherein administration of such composition results in increased expression of functional therapeutic protein or increased concentrations of functional therapeutic protein in the bloodstream of the subject. In a preferred embodiment, the subject in need is a human. In one embodiment, the composition is formulated for intravenous (IV) administration. In one aspect of the present invention, administration of the composition results in expression of the therapeutic protein in the bloodstream of the juvenile subject, preferably to at least about 5%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%, 110%, 120%, 130%, 140%, or 150% of the level of the therapeutic protein found in a normal juvenile subject. In certain embodiments, administration of the composition results in expression of at least about at least about 5%, 10%, 15%, 20%, 25%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%, 110%, 120%, 130%, 140%, or 150% of the level of the therapeutic protein found in a normal juvenile subject in the bloodstream of the juvenile subject 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, or more weeks after administration.

[0064] Other embodiments of the present invention will be evident to one skilled in the art upon reading the present patent specification.

DESCRIPTION OF DRAWINGS

[0065] FIG. 1A and 1B provides an illustration and chart of the study design, respectively. In brief, control adult mice (8 weeks old) were given a single dose of AAV5-FVIII-SQ (3.5E13

vg/kg which is approximately 8.9×10^{11} vg per mouse). Juvenile mice (2 days old) were divided into two cohorts. One cohort received a single dose of AAV5-FVIII-SQ that was the same total vg as adult mice (8.9×10^{11} vg/mouse). The other cohort received a single dose of AAV5-FVIII-SQ that was the same vg/kg as adult mice (3.5×10^{13} vg/kg).

[0066] FIG. 2 is a set of graphs that show that juveniles (dosed with same total vg as adults) have the same capacity as adults to take up AAV viral DNA as shown by total liver Factor VIII DNA in the left hand graph and total Factor VIII RNA in liver in the right hand graph.

[0067] FIG. 3 is a set of graphs that show that both body weight (left hand graph) and liver weight (right hand graph) of juvenile mice increased rapidly after AAV5-FVIII-SQ administration.

[0068] FIG. 4 is a graph that shows that AAV5-FVIII-SQ did not cause liver injury in juvenile mice, as determined by ALT measurement.

[0069] FIG. 5 is a set of graphs that show that juvenile mice need the same total amount of vector genome as adults to maintain therapeutic Factor VIII levels in adulthood. The left panel shows plasma Factor VIII concentration over time and the right panel shows total circulating Factor VIII in juvenile mice dosed with the same total amount of vector genome as adults (8.9×10^{11} vg/mouse which is equivalent to approximately 4.5×10^{14} vg/kg) or the vg per body weight as adults (3.5×10^{13} vg/kg). In both, these values are compared to adults treated with 3.5×10^{13} vg/kg. Total circulating FVIII was determined by multiplying plasma FVIII concentration by the estimated blood volume (in this case the estimated blood volume is 10% of body weight).

[0070] FIG. 6A & 6B. Figure 6A is immunohistochemical analysis of AAV5 capsid in liver sections from adult mice treated with AAV5-FVIII-SQ. Figure 6B is western blot analysis of AAV5 capsid from juvenile mice treated with AAV5-FVIII-SQ.

[0071] FIG. 7 is a table showing the overall design of a study that will determine the optimal conditions for expressing PAH in the livers of PKU subjects.

[0072] FIG. 8A-8C provide the body weight (g; mean $\pm$ SEM) for each group of AAV- and vehicle treated all ENU mice prior to and 8 weeks after dosing with 2×10^{14} vg/kg of AAV5-PAH or vehicle. Figure 8A provides the body weight prior to treatment. Figure 8B provides the body

weight 4 weeks post dosing. Figure 8C provides the body weight 8 weeks post dosing. * $p < 0.05$, **** $p, 0.0001$ as determined by one-way ANOVA.

[0073] FIG. 9A-9B provide the plasma PHE concentration (μM ; mean $\pm$ SEM) for each group of AAV- and vehicle treated all ENU mice prior to and 8 weeks after dosing with 2×10^{14} vg/kg of AAV5-PAH or vehicle. Figure 9A provides the plasma PHE concentration 4 weeks after dosing. Figure 9B provides the plasma PHE concentration 8 weeks post dosing. * $p < 0.05$, **** $p, 0.0001$ as determined by one-way ANOVA.

DETAILED DESCRIPTION

[0074] The present invention provides for AAV vectors encoding functionally active therapeutic proteins (e.g., completely packaged AAV Factor VIII vectors, AAV Factor IX vectors, and AAV PAH vectors). The recombinant AAV therapeutic protein vectors of the invention have improved transgene expression, as well as improved AAV virus production yield and simplified purification. Introducing one or more introns into the therapeutic protein-coding region enhances expression. Reconfiguring the number and positioning of enhancers also enhances expression.

AAV Vectors

[0075] As used herein, the term "AAV" is a standard abbreviation for adeno-associated virus. Adeno-associated virus is a single-stranded DNA parvovirus that grows only in cells in which certain functions are provided by a co-infecting helper virus. There are currently thirteen serotypes of AAV that have been characterized. General information and reviews of AAV can be found in, for example, Carter, 1989, Handbook of Parvoviruses, Vol. 1, pp. 169-228; and Berns, 1990, Virology, pp. 1743-1764, Raven Press, (New York). However, it is fully expected that these same principles will be applicable to additional AAV serotypes since it is well known that the various serotypes are quite closely related, both structurally and functionally, even at the genetic level. (See, e.g., Blacklowe, 1988, pp. 165-174 of Parvoviruses and Human Disease, J. R. Pattison, ed.; and Rose, Comprehensive Virology 3:1-61 (1974)). For example, all AAV serotypes apparently exhibit very similar replication properties mediated by homologous rep genes; and all bear three related capsid proteins. The degree of relatedness is further suggested by heteroduplex analysis which reveals extensive cross-hybridization between serotypes along

the length of the genome; and the presence of analogous self-annealing segments at the termini that correspond to "inverted terminal repeat sequences" (ITRs). The similar infectivity patterns also suggest that the replication functions in each serotype are under similar regulatory control.

[0076] An "AAV vector" as used herein refers to a vector comprising one or more polynucleotides of interest (or transgenes) that are flanked by AAV terminal repeat sequences (ITRs) and operably linked to one or more expression control elements. Such AAV vectors can be replicated and packaged into infectious viral particles when present in a host cell that has been transfected with a vector encoding and expressing rep and cap gene products.

[0077] An "AAV virion" or "AAV viral particle" or "AAV vector particle" refers to a viral particle composed of at least one AAV capsid protein and an encapsidated polynucleotide AAV 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 "AAV vector particle" or simply an "AAV vector." Thus, production of AAV vector particle necessarily includes production of AAV vector, as such a vector is contained within an AAV vector particle.

[0078] AAV "rep" and "cap" genes are genes encoding replication and encapsidation proteins, respectively. AAV rep and cap genes have been found in all AAV serotypes examined to date, and are described herein and in the references cited. In wild-type AAV, the rep and cap genes are generally found adjacent to each other in the viral genome (i.e., they are "coupled" together as adjoining or overlapping transcriptional units), and they are generally conserved among AAV serotypes. AAV rep and cap genes are also individually and collectively referred to as "AAV packaging genes." The AAV cap genes in accordance with the present invention encode Cap proteins which are capable of packaging AAV vectors in the presence of rep and adeno helper function and are capable of binding target cellular receptors. In some embodiments, the AAV cap gene encodes a capsid protein having an amino acid sequence derived from a particular AAV serotype.

[0079] The AAV sequences employed for the production of AAV can be derived from the genome of any AAV serotype. Generally, the AAV serotypes have genomic sequences of significant homology at the amino acid and the nucleic acid levels, provide a similar set of genetic functions, produce virions which are essentially physically and functionally equivalent,

and replicate and assemble by practically identical mechanisms. For the genomic sequence of AAV serotypes and a discussion of the genomic similarities. (*See, e.g.*, GenBank Accession number U89790; GenBank Accession number J01901; GenBank Accession number AF043303; GenBank Accession number AF085716; Chiorini et al., *J. Vir.* (1997) vol. 71, pp. 6823-6833; Srivastava et al., *J. Vir.* (1983) vol. 45, pp. 555-564; Chiorini et al., *J. Vir.* (1999) vol. 73, pp. 1309-1319; Rutledge et al., *J. Vir.* (1998) vol. 72, pp. 309-319; and Wu et al., *J. Vir.* (2000) vol. 74, pp. 8635-8647).

[0080] The genomic organization of all known AAV serotypes is very similar. The genome of AAV is a linear, single-stranded DNA molecule that is less than about 5,000 nucleotides (nt) in length. Inverted terminal repeats (ITRs) flank the unique coding nucleotide sequences for the non-structural replication (Rep) proteins and the structural (VP) proteins. The VP proteins form the capsid. The terminal 145 nt are self-complementary and are organized so that an energetically stable intramolecular duplex forming a T-shaped hairpin may be formed. These hairpin structures function as an origin for viral DNA replication, serving as primers for the cellular DNA polymerase complex. The Rep genes encode the Rep proteins, Rep78, Rep68, Rep52, and Rep40. Rep78 and Rep68 are transcribed from the p5 promoter, and Rep 52 and Rep40 are transcribed from the p19 promoter. The cap genes encode the VP proteins, VP1, VP2, and VP3. The cap genes are transcribed from the p40 promoter. The ITRs employed in the vectors of the present invention may correspond to the same serotype as the associated cap genes, or may differ. In a particularly preferred embodiment, the ITRs employed in the vectors of the present invention correspond to an AAV2 serotype and the cap genes correspond to an AAV5 serotype.

[0081] In some embodiments, a nucleic acid sequence encoding an AAV capsid protein is operably linked to expression control sequences for expression in a specific cell type, such as Sf9 or HEK cells. Techniques known to one skilled in the art for expressing foreign genes in insect host cells or mammalian host cells can be used to practice the invention. Methodology for molecular engineering and expression of polypeptides in insect cells is described, for example, in Summers and Smith (1986) *A Manual of Methods for Baculovirus Vectors and Insect Culture Procedures*, Texas Agricultural Experimental Station Bull. No. 7555, College Station, Tex.; Luckow (1991) In Prokop et al., *Cloning and Expression of Heterologous Genes in Insect Cells with Baculovirus Vectors* 'Recombinant DNA Technology and Applications, 97-152; King, L. A.

and R. D. Possee (1992) The baculovirus expression system, Chapman and Hall, United Kingdom; O'Reilly, D. R., L. K. Miller, V. A. Luckow (1992) Baculovirus Expression Vectors: A Laboratory Manual, New York; W.H. Freeman and Richardson, C. D. (1995) Baculovirus Expression Protocols, Methods in Molecular Biology, volume 39; U.S. Pat. No. 4,745,051; US2003148506; and WO 03/074714, all of which are incorporated by reference in their entireties. A particularly suitable promoter for transcription of a nucleotide sequence encoding an AAV capsid protein is e.g. the polyhedron promoter. However, other promoters that are active in insect cells are known in the art, e.g. the p10, p35 or IE-1 promoters and further promoters described in the above references are also contemplated.

[0082] Use of insect cells for expression of heterologous proteins is well documented, as are methods of introducing nucleic acids, such as vectors, e.g., insect-cell compatible vectors, into such cells and methods of maintaining such cells in culture. (*See, e.g., METHODS IN MOLECULAR BIOLOGY*, ed. Richard, Humana Press, N J (1995); O'Reilly et al., *BACULOVIRUS EXPRESSION VECTORS, A LABORATORY MANUAL*, Oxford Univ. Press (1994); Samulski et al., *J. Vir.* (1989) vol. 63, pp.3822-3828; Kajigaya et al., *Proc. Nat'l. Acad. Sci. USA* (1991) vol. 88, pp. 4646-4650; Ruffing et al., *J. Vir.* (1992) vol. 66, pp. 6922-6930; Kirnbauer et al., *Vir.* (1996) vol. 219, pp. 37-44; Zhao et al., *Vir.* (2000) vol. 272, pp. 382-393; and U.S. Pat. No. 6,204,059). In some embodiments, the nucleic acid construct encoding AAV in insect cells is an insect cell-compatible vector. An "insect cell-compatible vector" or "vector" as used herein refers to a nucleic acid molecule capable of productive transformation or transfection of an insect or insect cell. Exemplary biological vectors include plasmids, linear nucleic acid molecules, and recombinant viruses. Any vector can be employed as long as it is insect cell-compatible. The vector may integrate into the insect cells genome but the presence of the vector in the insect cell need not be permanent and transient episomal vectors are also included. The vectors can be introduced by any means known, for example by chemical treatment of the cells, electroporation, or infection. In some embodiments, the vector is a baculovirus, a viral vector, or a plasmid. In a more preferred embodiment, the vector is a baculovirus, i.e. the construct is a baculoviral vector. Baculoviral vectors and methods for their use are described in the above cited references on molecular engineering of insect cells.

[0083] Baculoviruses are enveloped DNA viruses of arthropods, two members of which are well known expression vectors for producing recombinant proteins in cell cultures.

Baculoviruses have circular double-stranded genomes (80-200 kbp) which can be engineered to allow the delivery of large genomic content to specific cells. The viruses used as a vector are generally *Autographa californica* multicapsid nucleopolyhedrovirus (AcMNPV) or *Bombyx mori* (Bm)NPV).

[0084] Baculoviruses are commonly used for the infection of insect cells for the expression of recombinant proteins. In particular, expression of heterologous genes in insects can be accomplished as described in for instance U.S. Pat. No. 4,745,051; Friesen et al (1986); EP 127,839; EP 155,476; Vlcek et al (1988); Miller et al (1988); Carbonell et al (1988); Maeda et al (1985); Lebacqz-Verheyden et al (1988); Smith et al (1985); Miyajima et al (1987); and Martin et al (1988). Numerous baculovirus strains and variants and corresponding permissive insect host cells that can be used for protein production are described in Luckow et al (1988), Miller et al (1986); Maeda et al (1985) and McKenna (1989).

Methods for Producing Recombinant AAVs

[0085] The present disclosure provides materials and methods for producing recombinant AAVs in insect or mammalian cells. In some embodiments, the viral construct further comprises a promoter and a restriction site downstream of the promoter to allow insertion of a polynucleotide encoding one or more proteins of interest, wherein the promoter and the restriction site are located downstream of the 5' AAV ITR and upstream of the 3' AAV ITR. In some embodiments, the viral construct further comprises a posttranscriptional regulatory element downstream of the restriction site and upstream of the 3' AAV ITR. In some embodiments, the viral construct further comprises a polynucleotide inserted at the restriction site and operably linked with the promoter, where the polynucleotide comprises the coding region of a protein of interest. As a skilled artisan will appreciate, any one of the AAV vector disclosed in the present application can be used in the method as the viral construct to produce the recombinant AAV.

[0086] In some embodiments, the helper functions are provided by one or more helper plasmids or helper viruses comprising adenoviral or baculoviral helper genes. Non-limiting examples of the adenoviral or baculoviral helper genes include, but are not limited to, E1A, E1B, E2A, E4 and VA, which can provide helper functions to AAV packaging.

[0087] Helper viruses of AAV are known in the art and include, for example, viruses from the family Adenoviridae and the family Herpesviridae. Examples of helper viruses of AAV include,

but are not limited to, SAdV-13 helper virus and SAdV-13-like helper virus described in US Publication No. 20110201088 (the disclosure of which is incorporated herein by reference), helper vectors pHELP (Applied Viromics). A skilled artisan will appreciate that any helper virus or helper plasmid of AAV that can provide adequate helper function to AAV can be used herein.

[0088] In some embodiments, the AAV cap genes are present in a plasmid. The plasmid can further comprise an AAV rep gene which may or may not correspond to the same serotype as the cap genes. The cap genes and/or rep gene from any AAV serotype (including, but not limited to, AAV1, AAV2, AAV4, AAV5, AAV6, AAV7, AAV8, AAV9, AAV10, AAV11, AAV12, AAV13 and any variants thereof) can be used herein to produce the recombinant AAV. In some embodiments, the AAV cap genes encode a capsid from serotype 1, serotype 2, serotype 4, serotype 5, serotype 6, serotype 7, serotype 8, serotype 9, serotype 10, serotype 11, serotype 12, serotype 13 or a variant thereof.

[0089] In some embodiments, the insect or mammalian cell can be transfected with the helper plasmid or helper virus, the viral construct and the plasmid encoding the AAV cap genes; and the recombinant AAV virus can be collected at various time points after co-transfection. For example, the recombinant AAV virus can be collected at about 12 hours, about 24 hours, about 36 hours, about 48 hours, about 72 hours, about 96 hours, about 120 hours, or a time between any of these two time points after the co-transfection.

[0090] Recombinant AAV can also be produced using any conventional methods known in the art suitable for producing infectious recombinant AAV. In some instances, a recombinant AAV can be produced by using an insect or mammalian cell that stably expresses some of the necessary components for AAV particle production. For example, a plasmid (or multiple plasmids) comprising AAV rep and cap genes, and a selectable marker, such as a neomycin resistance gene, can be integrated into the genome of the cell. The insect or mammalian cell can then be co-infected with a helper virus (e.g., adenovirus or baculovirus providing the helper functions) and the viral vector comprising the 5' and 3' AAV ITR (and the nucleotide sequence encoding the heterologous protein, if desired). The advantages of this method are that the cells are selectable and are suitable for large-scale production of the recombinant AAV. As another non-limiting example, adenovirus or baculovirus rather than plasmids can be used to introduce rep and cap genes into packaging cells. As yet another non-limiting example, both the viral

vector containing the 5' and 3' AAV LTRs and the rep-cap genes can be stably integrated into the DNA of producer cells, and the helper functions can be provided by a wild-type adenovirus to produce the recombinant AAV.

Cell Types Used in AAV Production

[0091] The viral particles comprising the AAV vectors of the invention may be produced using any invertebrate cell type which allows for production of AAV or biologic products and which can be maintained in culture. For example, the insect cell line used can be from *Spodoptera frugiperda*, such as SF9, SF21, SF900+, drosophila cell lines, mosquito cell lines, e.g., *Aedes albopictus* derived cell lines, domestic silkworm cell lines, e.g. *Bombyx mori* cell lines, *Trichoplusia ni* cell lines such as High Five cells or *Lepidoptera* cell lines such as *Ascalapha odorata* cell lines. Preferred insect cells are cells from the insect species which are susceptible to baculovirus infection, including High Five, Sf9, Se301, SeIZD2109, SeUCR1, Sf9, Sf900+, Sf21, BTI-TN-5B1-4, MG-1, Tn368, HzAm1, BM-N, Ha2302, Hz2E5 and Ao38.

[0092] Baculoviruses are enveloped DNA viruses of arthropods, two members of which are well known expression vectors for producing recombinant proteins in cell cultures. Baculoviruses have circular double-stranded genomes (80-200 kbp) which can be engineered to allow the delivery of large genomic content to specific cells. The viruses used as a vector are generally *Autographa californica* multicapsid nucleopolyhedrovirus (AcMNPV) or *Bombyx mori* (Bm-NPV) (Kato et al., 2010).

[0093] Baculoviruses are commonly used for the infection of insect cells for the expression of recombinant proteins. In particular, expression of heterologous genes in insects can be accomplished as described in for instance U.S. Pat. No. 4,745,051; Friesen et al (1986); EP 127,839; EP 155,476; Vlak et al (1988); Miller et al (1988); Carbonell et al (1988); Maeda et al (1985); Lebacqz-Verheyden et al (1988); Smith et al (1985); Miyajima et al (1987); and Martin et al (1988). Numerous baculovirus strains and variants and corresponding permissive insect host cells that can be used for protein production are described in Luckow et al (1988), Miller et al (1986); Maeda et al (1985) and McKenna (1989).

[0094] In another aspect of the invention, the methods of the invention are also carried out with any mammalian cell type which allows for replication of AAV or production of biologic products, and which can be maintained in culture. Preferred mammalian cells used can be

HEK293, HeLa, CHO, NSO, SP2/0, PER.C6, Vero, RD, BHK, HT 1080, A549, Cos-7, ARPE-19, and MRC-5 cells.

Pharmaceutical Formulations

[0095] In other embodiments, the present invention is directed to pharmaceutical formulations of therapeutic protein expressing AAV vectors/virions useful for administration to subjects suffering from a genetic disorder. In certain aspects, the pharmaceutical formulations of the present invention are liquid formulations that comprise recombinant therapeutic protein expressing AAV virions produced from the vectors disclosed herein, wherein the concentration of recombinant AAV virions in the formulation may vary widely. In certain embodiments, the concentration of recombinant AAV virion in the formulation may range from 1E12 vg/ml to 2E16 vg/ml. In a particularly preferred embodiment, the concentration of recombinant AAV virion in the formulation is about 2E13 vg/ml. In a preferred embodiment, the recombinant AAV virion present in the formulation is derived from AAV5-FVIII-SQ. In other preferred embodiments of the invention the recombinant AAV virion present in the formulation is derived from AAV vectors expressing Factor IX or expressing PAH.

[0096] In other aspects, the AAV pharmaceutical formulation of the invention comprises one or more pharmaceutically acceptable excipients to provide the formulation with advantageous properties for storage and/or administration to subjects for the treatment of the genetic disorder. In certain embodiments, the pharmaceutical formulations of the present invention are capable of being stored at -65°C for a period of at least 2 weeks, preferably at least 4 weeks, more preferably at least 6 weeks and yet more preferably at least about 8 weeks, without detectable change in stability. In this regard, the term "stable" means that the recombinant AAV virus present in the formulation essentially retains its physical stability, chemical stability and/or biological activity during storage. In certain embodiments of the present invention, the recombinant AAV virus present in the pharmaceutical formulation retains at least about 80% of its biological activity in a human patient during storage for a determined period of time at -65°C, more preferably at least about 85%, 90%, 95%, 98% or 99% of its biological activity in a juvenile human subject.

[0097] In certain aspects, the formulation comprising recombinant AAV virions further comprises one or more buffering agents. For example, in various aspects, the formulation of the

present invention comprises sodium phosphate dibasic at a concentration of about 0.1 mg/ml to about 3 mg/ml, about 0.5 mg/ml to about 2.5 mg/ml, about 1 mg/ml to about 2 mg/ml, or about 1.4 mg/ml to about 1.6 mg/ml. In a particularly preferred embodiment, the AAV formulation of the present invention comprises about 1.42 mg/ml of sodium phosphate, dibasic (dried). Another buffering agent that may find use in the recombinant AAV formulations of the present invention is sodium phosphate, monobasic monohydrate which, in some embodiments, finds use at a concentration of from about 0.1 mg/ml to about 3 mg/ml, about 0.5 mg/ml to about 2.5 mg/ml, about 1 mg/ml to about 2 mg/ml, or about 1.3 mg/ml to about 1.5 mg/ml. In a particularly preferred embodiment, the AAV formulation of the present invention comprises about 1.38 mg/ml of sodium phosphate, monobasic monohydrate. In a yet more particularly preferred embodiment of the present invention, the recombinant AAV formulation of the present invention comprises about 1.42 mg/ml of sodium phosphate, dibasic and about 1.38 mg/ml of sodium phosphate, monobasic monohydrate.

[0098] In another aspect, the recombinant AAV formulation of the present invention may comprise one or more isotonicity agents, such as sodium chloride, preferably at a concentration of about 1 mg/ml to about 20 mg/ml, for example, about 1 mg/ml to about 10 mg/ml, about 5 mg/ml to about 15 mg/ml, or about 8 mg/ml to about 20 mg/ml. In a particularly preferred embodiment, the formulation of the present invention comprises about 8.18 mg/ml sodium chloride. Other buffering agents and isotonicity agents known in the art are suitable and may be routinely employed for use in the formulations of the present disclosure.

[0099] In another aspect, the recombinant AAV formulations of the present invention may comprise one or more bulking agents. Exemplary bulking agents include without limitation mannitol, sucrose, dextran, lactose, trehalose, and povidone (PVP K24). In certain preferred embodiments, the formulations of the present invention comprise mannitol, which may be present in an amount from about 5 mg/ml to about 40 mg/ml, or from about 10 mg/ml to about 30 mg/ml, or from about 15 mg/ml to about 25 mg/ml. In a particularly preferred embodiment, mannitol is present at a concentration of about 20 mg/ml.

[00100] In yet another aspect, the recombinant AAV formulations of the present invention may comprise one or more surfactants, which may be non-ionic surfactants. Exemplary surfactants include ionic surfactants, non-ionic surfactants, and combinations thereof. For

example, the surfactant can be, without limitation, TWEEN 80 (also known as polysorbate 80, or its chemical name polyoxyethylene sorbitan monooleate), sodium dodecylsulfate, sodium stearate, ammonium lauryl sulfate, TRITON AG 98 (Rhone-Poulenc), poloxamer 407, poloxamer 188 and the like, and combinations thereof. In a particularly preferred embodiment, the formulation of the present invention comprises poloxamer 188, which may be present at a concentration of from about 0.1 mg/ml to about 4 mg/ml, or from about 0.5 mg/ml to about 3 mg/ml, from about 1 mg/ml to about 3 mg/ml, about 1.5 mg/ml to about 2.5 mg/ml, or from about 1.8 mg/ml to about 2.2 mg/ml. In a particularly preferred embodiment, poloxamer 188 is present at a concentration of about 2.0 mg/ml.

[00101] In a particular preferred embodiment of the present invention, the pharmaceutical formulation of the present invention comprises AAV5-FVIII-SQ formulated in a liquid solution that comprises about 1.42 mg/ml of sodium phosphate, dibasic, about 1.38 mg/ml of sodium phosphate, monobasic monohydrate, about 8.18 mg/ml sodium chloride, about 20 mg/ml mannitol and about 2 mg/ml poloxamer 188.

[00102] The recombinant therapeutic protein expressing AAV virus-containing formulations of the present disclosure are stable and can be stored for extended periods of time without an unacceptable change in quality, potency, or purity. In one aspect, the formulation is stable at a temperature of about 5°C (e.g., 2°C to 8°C) for at least 1 month, for example, at least 1 month, at least 3 months, at least 6 months, at least 12 months, at least 18 months, at least 24 months, or more. In another aspect, the formulation is stable at a temperature of less than or equal to about -20°C for at least 6 months, for example, at least 6 months, at least 12 months, at least 18 months, at least 24 months, at least 36 months, or more. In another aspect, the formulation is stable at a temperature of less than or equal to about -40°C for at least 6 months, for example, at least 6 months, at least 12 months, at least 18 months, at least 24 months, at least 36 months, or more. In another aspect, the formulation is stable at a temperature of less than or equal to about -60°C for at least 6 months, for example, at least 6 months, at least 12 months, at least 18 months, at least 24 months, at least 36 months, or more.

Methods of Treatment

[00103] In certain embodiments, the present invention is directed to methods for treating a subject suffering from a genetic disorder comprising administering to that subject a

therapeutically effective amount of an AAV vector expressing a therapeutic protein or a pharmaceutical composition comprising the same. In this instance, a “therapeutically effective amount” is an amount of AAV vector that after administration results in the expression of the therapeutic protein in a level sufficient to at least partially and preferably fully ameliorate the symptoms of the genetic disorder.

[00104] For example, the present invention is directed to methods of treating diseases or disorders including cancer such as carcinoma, sarcoma, leukemia, lymphoma; and autoimmune diseases such as multiple sclerosis. Non-limiting examples of carcinomas include esophageal carcinoma; hepatocellular carcinoma; basal cell carcinoma, squamous cell carcinoma (various tissues); bladder carcinoma, including transitional cell carcinoma; bronchogenic carcinoma; colon carcinoma; colorectal carcinoma; gastric carcinoma; lung carcinoma, including small cell carcinoma and non-small cell carcinoma of the lung; adrenocortical carcinoma; thyroid carcinoma; pancreatic carcinoma; breast carcinoma; ovarian carcinoma; prostate carcinoma; adenocarcinoma; sweat gland carcinoma; sebaceous gland carcinoma; papillary carcinoma; papillary adenocarcinoma; cystadenocarcinoma; medullary carcinoma; renal cell carcinoma; ductal carcinoma in situ or bile duct carcinoma; choriocarcinoma; seminoma; embryonal carcinoma; Wilm's tumor; cervical carcinoma; uterine carcinoma; testicular carcinoma; osteogenic carcinoma; epithelial carcinoma; and nasopharyngeal carcinoma. Non-limiting examples of sarcomas include fibrosarcoma, myxosarcoma, liposarcoma, chondrosarcoma, chordoma, osteogenic sarcoma, osteosarcoma, angiosarcoma, endotheliosarcoma, lymphangiosarcoma, lymphangioendotheliosarcoma, synovioma, mesothelioma, Ewing's sarcoma, leiomyosarcoma, rhabdomyosarcoma, and other soft tissue sarcomas. Non-limiting examples of solid tumors include glioma, astrocytoma, medulloblastoma, craniopharyngioma, ependymoma, pinealoma, hemangioblastoma, acoustic neuroma, oligodendroglioma, meningioma, melanoma, neuroblastoma, and retinoblastoma. Non-limiting examples of leukemias include chronic myeloproliferative syndromes; acute myelogenous leukemias; chronic lymphocytic leukemias, including B-cell CLL, T-cell CLL, prolymphocytic leukemia, and hairy cell leukemia; and acute lymphoblastic leukemias. Examples of lymphomas include, but are not limited to, B-cell lymphomas, such as Burkitt's lymphoma; Hodgkin's lymphoma; and the like. Other non-limiting examples of the diseases that can be treated using the AAV vectors, recombinant viruses and methods disclosed herein include genetic disorders including sickle cell

anemia, cystic fibrosis, lysosomal acid lipase (LAL) deficiency 1, Tay-Sachs disease, Phenylketonuria, Mucopolysaccharidoses, Glycogen storage diseases (GSD, e.g., GSD types I, II, III, IV, V, VI, VII, VIII, IX, X, XI, XII, XIII, and XIV), Galactosemia, muscular dystrophy (e.g., Duchenne muscular dystrophy), Wilson's disease, hereditary angioedema (HAE), alpha 1 antitrypsin deficiency, Fabry Disease, Gaucher Disease and hemophilia such as hemophilia A (classic hemophilia) and hemophilia B (Christmas Disease). In addition, the AAV vectors, recombinant viruses and methods disclosed herein can be used to other disorders that can be treated by local expression of a transgene in the liver or by expression of a secreted protein from the liver or a hepatocyte.

[00105] In a preferred embodiment, the present invention is directed to methods for reducing bleeding time during a bleeding episode in a juvenile subject suffering from hemophilia A comprising administering to that juvenile subject a therapeutically effective amount of an AAV FVIII vector, recombinant AAV FVIII virus or a pharmaceutical composition comprising the same. In this regard, a "therapeutically effective amount", in reference to the treatment of hemophilia A or for use in a method for reducing bleeding time during a bleeding episode in a subject suffering from hemophilia A, refers to an amount capable of invoking one or more of the following effects: (1) reduction, inhibition, or prevention, to some extent, of one or more of the physiological symptoms of hemophilia A including, for example, bruising, joint pain or swelling, prolonged headache, vomiting or fatigue, (2) improvement in the capability to clot blood, (3) reduction of overall bleeding time during a bleeding episode, (4) administration resulting in a measurable increase in the concentration or activity of functional FVIII protein in the plasma of a subject, and/or (5) relief, to some extent, of one or more symptoms associated with the disorder.

[00106] A "therapeutically effective amount" of an AAV vector or virus or a pharmaceutical composition comprising the same for purposes of treatment as described herein may be determined empirically and in a routine manner. In a particularly preferred embodiment, a therapeutically effective amount of a therapeutic AAV virus for treatment of a juvenile subject is the same absolute number of viral particles that has been determined, calculated, or estimated to produce a therapeutic response in adult subjects. Accordingly, the invention provides administering AAV vectors to juvenile subjects at higher doses compared to adults when measured as vg/kg body weight. In some embodiments this corresponds to 2 to 15 times the amount of AAV vector given to an adult when expressed as vg/kg. In certain embodiments,

however, a "therapeutically effective amount" of recombinant AAV virus ranges from about 1E12 vg/kg body weight to about 1E14 vg/kg body weight, preferably from about 6E12 vg/kg body weight to about 6E13 vg/kg body weight. In a preferred embodiment, a therapeutically effective amount of recombinant AAV virus is about 2E13 vg/kg body weight. In another preferred embodiment, a therapeutically effective amount of recombinant AAV virus is about 6E13 vg/kg body weight.

[00107] Recombinant AAV vectors/virus of the present invention may be administered to a juvenile subject, preferably a juvenile mammalian subject, more preferably a juvenile human subject, through a variety of known administration techniques. In a preferred embodiment, the recombinant AAV gene therapy virus is administered by intravenous injection either as a single bolus or over a prolonged time period, which may be at least about 1, 5, 10, 15, 30, 45, 60, 75, 90, 120, 150, 180, 210 or 240 minutes, or more. In preferred embodiments the recombinant AAV virus administered expresses Factor VIII, Factor IX, or PAH. In a particularly preferred embodiment of the present invention, the recombinant AAV virus administered is AAV5-FVIII-SQ.

[00108] Administration of a recombinant AAV FVIII vector/virus, or pharmaceutical formulation comprising the same, of the present invention preferably results in an increase in functional FVIII protein activity in the plasma of the subject of at least 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, or more IU/dl as compared to the amount of functional FVIII protein activity present in the plasma in the subject prior to administration. In certain embodiments, administration of a recombinant AAV FVIII vector/virus, or pharmaceutical formulation comprising the same, of the present invention results in the expression of at least about 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 or more IU/dl of functional FVIII protein activity in the plasma of the subject. In this regard, the term "IU" or "international unit" in regards to FVIII activity is a well understood and accepted term, wherein 1 IU of FVIII activity is equivalent to the quantity of FVIII in one ml of normal human plasma. FVIII activity in the plasma may be quantitatively determined by a number of well-known and accepted assays including, for example, the activated partial thromboplastin time (APPT) method (*see, e.g.*, Miletich JP: Activated partial thromboplastin time. In Williams Hematology. Fifth edition. Edited by E Beutler, M A Lichtman, B A Coller, T J Kipps. New York, McGraw-Hill, 1995, pp L85-86, Greaves and Preston, Approach to the bleeding patient. In Hemostasis and Thrombosis: Basic Principles and Clinical Practice. Fourth

edition. Edited by R W Colman, J Hirsh, V J Marder, et al. Philadelphia, JB Lippincott Co, 2001, pp 1197-1234 and Olson et al, (1998) *Arch. Pathol. Lab. Med.*, vol. 122, pp. 782-798) or chromogenic FXa assay (Harris et al., (2011) *Thromb. Res.*, vol. 128, pp. 125-129).

[00109] In other embodiments of the present invention, bleeding time in a subject may be measured by well-known and accepted techniques including, for example, the Ivy method (*see, e.g.*, Ivy et al., (1935) *Surg. Gynec. Obstet.*, vol. 60, page 781 (1935) and Ivy et al., (1941) *J. Lab. Clin. Med.*, vol. 26, page 1812) or the Duke method (*see, e.g.*, Duke et al., (1910) *JAMA*, vol. 55, page 1185). A "bleeding episode" in a subject refers to an injury that results in bleeding in the subject, either externally or internally, and generally comprises the time period from injury to formation of a blood clot.

[00110] In aspects of the invention involving an AAV vector expressing PAH to treat PKU in juvenile subjects, the effectiveness of the AAV vector can be monitored by measuring levels of phenylalanine in the blood of the treated juvenile subject. Precise quantitative assays for determining circulating levels of phenylalanine are well known in the art and include fluorometric assays (*see*, McCaman, M.W. and Robins, E., (1962) *J. Lab. Clin. Med.*, vol. 59, pp. 885-890); thin layer chromatography based assays (*see*, Tsukerman, G. L. (1985) *Laboratorio delo*, vol. 6, pp. 326-327); enzymatic assays (*see*, La Du, B. N., et al. (1963) *Pediatrics*, vol. 31, pp. 39-46; and Peterson, K., et al. (1988) *Biochem. Med. Metab. Biol.*, vol. 39, pp. 98-104); methods employing high pressure liquid chromatography (HPLC) (*see*, Rudy, J. L., et al. (1987) *Clin. Chem.*, vol. 33, pp. 1152-1154); and high-throughput automation (*see*, Hill, J. B., et al. (1985) *Clin. Chem.*, vol. 5, pp. 541-546).

[00111] Administration of an AAV virus of the present invention may, in some cases, result in an observable degree of hepatotoxicity. Hepatotoxicity may be measured by a variety of well-known and routinely used techniques for example, measuring concentrations of certain liver-associated enzyme(s) (e.g., alanine transaminase, ALT) in the bloodstream of a subject both prior to AAV administration (i.e., baseline) and after AAV administration. An observable increase in ALT concentration after AAV administration (as compared to prior to administration) is indicative of drug-induced hepatotoxicity. In certain embodiments of the present invention, in addition to administration of a therapeutically effective amount of AAV virus, the subject may

be treated either prophylactically, therapeutically, or both with a corticosteroid to prevent and/or treat any hepatotoxicity associated with administration of the AAV virus.

[00112] "Prophylactic" corticosteroid treatment refers to the administration of a corticosteroid to prevent hepatotoxicity and/or to prevent an increase in measured ALT levels in the subject. "Therapeutic" corticosteroid treatment refers to the administration of a corticosteroid to reduce hepatotoxicity caused by administration of an AAV virus and/or to reduce an elevated ALT concentration in the bloodstream of the subject caused by administration of an AAV virus. In certain embodiments, prophylactic or therapeutic corticosteroid treatment may comprise administration of at least 5, 10, 15, 20, 25, 30, 35, 40, 45, 50, 55, 60, or more mg/day of the corticosteroid to the subject. In certain embodiments, prophylactic or therapeutic corticosteroid treatment of a subject may occur over a continuous period of at least about 3, 4, 5, 6, 7, 8, 9, 10 weeks, or more. Corticosteroids that find use in the methods described herein include any known or routinely-employed corticosteroid including, for example, dexamethasone, prednisone, fludrocortisone, hydrocortisone, and the like.

Detection of Anti-AAV Antibodies

[00113] To maximize the likelihood of successful liver transduction with systemic AAV-mediated therapeutic gene transfer, prior to administration of an AAV vector in a therapeutic regimen to a human patient as described above, the prospective patient may be assessed for the presence of anti-AAV capsid antibodies that are capable of blocking cell transduction or otherwise reduce the overall efficiency of the therapeutic regimen. Such antibodies may be present in the serum of the prospective patient and may be directed against an AAV capsid of any serotype. In one embodiment, the serotype against which pre-existing antibodies are directed is AAV5.

[00114] Methods to detect pre-existing AAV immunity are well known and routinely employed in the art and include cell-based in vitro transduction inhibition (TI) assays, in vivo (e.g., in mice) TI assays, and ELISA-based detection of total anti-capsid antibodies (TAb) (*see, e.g., Masat et al., Discov. Med.*, vol. 15, pp. 379-389 and Boutin et al., (2010) *Hum. Gene Ther.*, vol. 21, pp. 704-712). TI assays may employ host cells into which an AAV-inducible reporter vector has been previously introduced. The reporter vector may comprise an inducible reporter gene such as GFP, etc. whose expression is induced upon transduction of the host cell by an

AAV virus. Anti-AAV capsid antibodies present in human serum that are capable of preventing/reducing host cell transduction would thereby reduce overall expression of the reporter gene in the system. Therefore, such assays may be employed to detect the presence of anti-AAV capsid antibodies in human serum that are capable of preventing/reducing cell transduction by the therapeutic FVIII AAV virus.

[00115] TAB assays to detect anti-AAV capsid antibodies may employ solid-phase-bound AAV capsid as a "capture agent" over which human serum is passed, thereby allowing anti-capsid antibodies present in the serum to bind to the solid-phase-bound capsid "capture agent". Once washed to remove non-specific binding, a "detection agent" may be employed to detect the presence of anti-capsid antibodies bound to the capture agent. The detection agent may be an antibody, an AAV capsid, or the like, and may be detectably-labeled to aid in detection and quantitation of bound anti-capsid antibody. In one embodiment, the detection agent is labeled with ruthenium or a ruthenium-complex that may be detected using electrochemiluminescence techniques and equipment.

[00116] The same above-described methodology may be employed to assess and detect the generation of an anti-AAV capsid immune response in a patient previously treated with a therapeutic AAV virus of interest. As such, not only may these techniques be employed to assess the presence of anti-AAV capsid antibodies prior to treatment with a therapeutic AAV virus, they may also be employed to assess and measure the induction of an immune response against the administered therapeutic AAV virus after administration. As such, the present invention contemplates methods that combine techniques for detecting anti-AAV capsid antibodies in human serum and administration of a therapeutic AAV virus for the treatment of hemophilia A, wherein the techniques for detecting anti-AAV capsid antibodies in human serum may be performed either prior to or after administration of the therapeutic AAV virus.

[00117] Other aspects and advantages of the present invention will be understood upon consideration of the following illustrative examples.

EXAMPLES

Example 1

AAV Age Comparison Study

[00118] To examine the ability of juvenile mice to respond to AAV mediated gene therapy, two doses of an AAV expressing human Factor VIII (AAV5-FVIII-SQ) were administered to two cohorts of juvenile (2 day old) Rag2/FVIII double knock-out mice (DKO). All doses were administered intravenously via tail veins. Adult (8 week old) Rag2/FVIII DKO mice were used as controls and were treated with 3.5×10^{13} vg/kg which in the adult corresponds to 8.9×10^{11} vg per mouse. Cohort 1 of the juvenile mice (2 days old) were treated with the same dose per body weight as adults (i.e. 3.5×10^{13} vg/kg) whereas cohort 2 of the juvenile mice (2 days old) were treated with the same absolute vg per mouse as adults (i.e. 8.9×10^{11} vg per mouse which corresponds to 4.5×10^{14} vg/kg in 2 day old mice). Figures 1A and 1B provide the study design and the sample collection time points. Groups of juvenile mice were studied well into adulthood (beyond 8 weeks of age) following AAV administration.

[00119] To determine the capacity of juvenile hepatocytes to take-up AAV5-FVIII-SQ, the amounts of FVIII DNA and FVIII RNA in the livers of treated juvenile and adult mice were measured. As shown in Figure 2, juvenile mice receiving the same total vg as adult mice (8.9×10^{11} vg per mouse; 4.5×10^{14} vg/kg body weight juvenile mice) had similar levels of FVIII DNA as adult mice demonstrating that there was no additional loss of DNA due to hepatocyte division in juvenile mice. This result was surprising in light of the literature on AAV vectors, which teaches that hepatocytes of juveniles treated with AAV lose viral genomes due to cell division and growth of the animal. In addition, as shown in Figure 2 (right hand graph) Factor VIII RNA levels increased over time in adult mice dosed with AAV5-FVIII-SQ. Surprisingly, juvenile mice dosed with the same absolute dose as the adult mice demonstrated a similar increase in Factor VIII RNA over time. These data demonstrate that juvenile hepatocytes have the same ability to take up AAV genomes and express AAV delivered transgenes as do adult hepatocytes and that juvenile hepatocytes, contrary to the teachings of the art, do not lose viral genomes during tissue growth and cell division.

[00120] The effect of AAV treatment on the overall health and development of the juvenile mice was assessed by measuring both body weight and liver weight over time after AAV

administration. As shown in Figure 3, both the liver weight and body weight of AAV treated juvenile mice increased over time and reached normal adult levels by 8 weeks post-administration. Further, to evaluate whether AAV treatment that targets transgene expression in liver resulted in liver injury, blood levels of alanine aminotransferase (ALT) were measured. As shown in Figure 4, ALT levels did not increase in response to AAV5-FVIII-SQ treatment despite the juvenile mice being given the same absolute amount of vector genome as adults, i.e. higher levels of vg per body weight than the control adult animals. Taken together, these data demonstrate that AAV treatment did not have a negative effect on overall health or development of juvenile mice and did not cause liver injury despite the relatively high levels of viral genomes being administered.

[00121] The therapeutic effectiveness of AAV delivered transgenes in juvenile mice were assessed by measuring the plasma Factor VIII concentration and estimating total circulating Factor VIII protein. As shown in Figure 5, juveniles treated with the same dose on a per body weight basis as adults (3.5×10^{13} vg/kg) did not produce therapeutic levels of Factor VIII when they reached adulthood. This result is consistent with prior studies demonstrating that juvenile hepatocytes stopped producing detectable levels of AAV administered transgenes several weeks after AAV administration. Surprisingly, juvenile mice dosed with the adult dose of absolute number of viral genomes (8.9×10^{11} vg), initially express high levels of plasma Factor VIII. These levels decreased between weeks 1 and 3 due to blood volume expansion. However, the total amount of circulating Factor VIII remained stable from week 1 to the end of the study at week 16. This maintained level of Factor VIII protein in juvenile mice, while five to six fold lower than levels seen in treated adult mice, remained within the therapeutically effective window. Accordingly, these data demonstrate that AAV are effective in delivering a therapeutic dose of a transgene when the AAV are administered at an adult dose of absolute viral genome amount per subject. Moreover, these data demonstrate that the transgene expression stabilizes and remains constant for long durations.

Example 2

Delivery and Expression of PAH in the livers of Juvenile PKU Subjects

[00122] In mammals, the liver enzyme phenylalanine hydroxylase (PAH) converts excess phenylalanine (Phe) in the body to tyrosine (Tyr). In humans, mutations in the gene coding for PAH can result in diminished or lack of production or activity of the enzyme, resulting in an accumulation of Phe and decrease of Tyr levels in the body, with phenotypic consequences, including growth failure, light skin and hair coloration, cognitive deficits, sleep disturbance, and seizures. In humans this disease state is called phenylketonuria (PKU). The ENU2 mouse model of PKU (Sheldovsky 1993) was created by chemical mutagenesis, using N-ethyl-N-nitrosourea (ENU), in exon 7 of the gene coding for PAH. Phe263 is replaced by Ser263, resulting in a mild reduction of PAH protein levels, but no detectable PAH catalytic activity. This is analogous to a mutation found in a large subset of human PKU patients where Phe263 has been mutated to Leu263. ENU2 mice have phenotypes which recapitulate several of those seen in PKU patients, including high plasma and tissue levels of Phe, low levels of Tyr, small size/body weight, a light brown coat color (while wild-type counterparts are black), and seizures.

[00123] Male ENU2 mice were enrolled into individual age groups (n=10/group) as listed below and injected intravenously with the AAV5-PAH at 2×10^{14} vg/kg at the approximate age: Group One, AAV administered at 2 days of age; Group Two, AAV administered at 1 week of age; Group Three, AAV administered at 2 weeks of age; Group Four, AAV administered at 3 weeks of age; Group Five, AAV administered at 5 weeks of age; and Group Six, AAV administered at 8 weeks of age (see Figure 7 for overall study design).

[00124] Body weights were measured prior to study start, and at four and eight weeks post-dose. Blood samples were collected 4 and 8 weeks post-dose, processed to plasma, and analyzed for Phe by liquid chromatography/mass spectrometry. Plasma proteins were precipitated using acetonitrile containing a stable isotope internal standards ($^{13}\text{C}_9, ^{15}\text{N}$ (PheIS)). The supernatant was derivatized by reaction with Benzoyl Chloride and diluted prior to LC-MS/MS injection.

[00125] Body weights of animals in each age group were similar prior to dosing (Fig 8A). Four weeks post dosing (Fig 8B), animals treated with AAV5-PAH at either 3 or 8 weeks of age, but not those treated at 2 days, or 1, 2, or 5 weeks of age gained significantly more weight

than their vehicle-treated counterparts. By 8 weeks post-dosing (Fig 8C), mice treated at 5 weeks of age also achieved significantly more weight gain than controls.

[00126] At both the 4 (Fig 9A) and 8-week (Fig 9B) time points, Phe levels were reduced to WT range in mice treated at 5 or 8 weeks of age. Mice treated at 3 weeks of age had more variable phe levels, suggesting a partial response. Mice treated at 2 days, 1 week, or 2 weeks of age did not have appreciable reduction in plasma Phe.

[00127] Maximal effect of treatment with AAV5PAH, 2E14 vg/kg, on the ENU2 phenotypes of low body weight and high plasma Phe was achieved when mice were at least 5 weeks old at time of treatment. A significant effect on body weight, but only a partial effect on Phe reduction, was achieved when mice were treated at 3 weeks of age.