ADENO-ASSOCIATED VIRUS FACTOR VIII VECTORS

[0001] This application claims priority to the U.S. Provisional Patent Application Serial No. 61/877,042, filed September 12, 2013, which is incorporated by reference herein its entirety.

FIELD OF INVENTION

[0002] The invention relates to adeno-associated virus (AAV) Factor VIII (FVIII) vectors, including AAV FVIII vectors with high expression activity and AAV FVIII vectors that express full-length or truncated functional FVIII. The invention also relates to methods of making the herein described AAV FVIII vectors and associated therapeutic uses of thereof.

BACKGROUND

[0003] 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 for the treatment of Hemophilia B (Nathwani et al., New Engl. J. Med. 365:2357-2365, 2011).

[0004] AAV gene therapy vectors do have some drawbacks, however. 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.

[0005] Due to this size constraint, large therapeutic genes, i.e., those greater than about 4.4 kb in length, are generally not suitable for use in AAV vectors. One such therapeutic gene is the Factor VIII (FVIII) gene, which has an mRNA of about 7.0 kb that encodes a polypeptide of 2332 amino acids comprising, from N- to C-terminus, a 19 amino acid signal peptide, and three

large domains (i.e., the heavy chain or A domain, the central or B domain, and the light chain or C domain). One strategy that had been employed to overcome the AAV vector size limitation for FVIII was to use two AAV vectors, one encoding the heavy chain or A domain, and the other encoding the light chain or C domain (see, e.g., Coutu et al., US Pat. Nos. 6,221349, 6,200,560 and 7,351,577). Another strategy to circumvent this size constraint was to generate AAV vectors encoding FVIII in which the central portion or B domain of the protein has been deleted and replaced with a 14 amino acid linker, known as the SQ sequence (Ward et al., Blood, 117:798-807, 2011, and McIntosh et al., Blood 121:3335-3344, 2013).

[0006] While AAV vectors have been reported in the literature having AAV genomes of > 5.0 kb, in many of these cases the 5' or 3' ends of the encoded genes appear to be truncated (see Hirsch et al., Molec. Ther. 18-6-8, 2010, and Ghosh et al., Biotech. Genet. Engin. Rev. 24:165-178, 2007). It has been shown, however, that overlapping homologous recombination occurs in AAV infected cells between nucleic acids having 5' end truncations and 3' end truncations so that a "complete" nucleic acid encoding the large protein is generated, thereby reconstructing a functional, full-length gene.

[0007] There is a need for novel AAV vectors encoding a functional Factor VIII protein useful in gene therapy approaches for the treatment of hemophilia A. As such, the present invention relates to AAV vectors that encode functionally active FVIII such that either the AAV virions encapsidate the entire nucleic acid encoding the therapeutic protein, i.e., completely packaged AAV FVIII vectors, thereby avoiding the above-mentioned problems of oversized genomes, or at least produce a functionally active Factor VIII protein, which may or may not be truncated. Moreover, to avoid capsid directed immune response, AAV vectors should have the highest possible transduction/expression activity of the target protein per capsid particle. This invention also relates to the production of completely AAV FVIII vectors with high expression activity. Finally, the present invention relates to methods for producing the herein described AAV Factor VIII vectors and associated methods for using the same.

SUMMARY OF INVENTION

[0008] The present invention provides AAV vectors encoding functionally active FVIII (referred to herein as "AAV FVIII vectors"). The genomes encoding functionally active FVIII 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.

[0009] As used herein, a "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. This includes, for example, allowing for blood coagulation to occur and decreasing 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 FIX (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.

[0010] 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 operably linked to transcription regulatory elements, i.e., one or more promoters and/or enhancers, and a polyadenylation sequence, and, optionally, 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 in provided in base pairs (bp).

[0011] 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. 79(1):364-379 (2005) which is herein incorporated by reference in its entirety.

[0012] 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.

[0012a] In one aspect, there is provided an adeno-associated virus (AAV) vector comprising an AAV2 5' inverted terminal repeat (ITR), a liver-specific transcription regulatory region, a functionally active FVIII coding region, a polyadenylation sequence, an AAV2 3' ITR, and optionally one or more introns, wherein said AAV vector is less than 5.0 kb in length, wherein the functionally active FVIII coding region comprises nucleotides 923-5296 of SEQ ID NO: 9.

[0013] In one example, the AAV vector of the disclosure comprises a nucleic acid encoding functionally active FVIII having the B domain replaced by the 14 amino acid SQ sequence, i.e., encoding FVIII SQ. The SQ sequence is disclosed in Ward et al., Blood, 117:798-807, 2011, and McIntosh et al., Blood 121:3335-3344, 2013. The FVIII coding region sequence is a codon-optimized sequence (see Nathwani et al., US Pat. App. Pub. No. 2013/0024960A1, published January 24, 2013, which is incorporated herein by reference in its entirety, and McIntosh et al., Blood 121:3335-3344, 2013). This sequence is referred herein as the "UCL SQ FVIII."

[0014] In one example, the AAV vector of the disclosure comprises Proto 1, which is depicted schematically in Figure 2A, and comprises the nucleic acid sequence set forth in SEQ ID NO: 1.

[0015] In one example, the AAV vector of the disclosure comprises Proto 1S, which is depicted schematically in Figure 2B, and comprises the nucleic acid sequence set forth in SEQ ID NO: 2.

[0016] In one example, the AAV vector of the disclosure comprises Proto 2S, which is depicted schematically in Figure 2C, and comprises the nucleic acid sequence set forth in SEQ ID NO: 3.

[0017] In one example, the AAV vector of the disclosure comprises Proto 3S, which is depicted schematically in Figure 2D, and comprises the nucleic acid sequence set forth in SEQ ID NO: 4.

[0018] In another example, the AAV vector of the disclosure comprises a nucleic acid encoding FVIII lacking the entire B domain, including the SQ sequence, and the a3 domain, which is located just N-terminal to the light chain or C domain. The FVIII coding region sequence is a codon-optimized sequence (see Nathwani et al., US Pat. App. Pub. No. 2013/0024960A1, published January 24, 2013, which is incorporated herein by reference in its entirety, and McIntosh et al., Blood 121:3335-3344, 2013).

[0019] In one example, the AAV vector of the disclosure comprises Proto 4, which is depicted schematically in Figure 3A, and comprises the nucleic acid sequence set forth in SEQ ID NO: 5.

[0020] In one example, the AAV vector of the disclosure comprises Proto 5, which is depicted schematically in Figure 3B, and comprises the nucleic acid sequence set forth in SEQ ID NO: 6.

[0021] In one example, the AAV vector of the disclosure comprises Proto 6, which is depicted schematically in Figure 3C, and comprises the nucleic acid sequence set forth inSEQ ID NO: 7.

[0022] In one example, the AAV vector of the disclosure comprises Proto 7, which is depicted schematically in Figure 3D, and comprises the nucleic acid sequence set forth in SEQ ID NO: 8.

[0023] In another example, the AAV vector of the disclosure comprises a nucleic acid comprising an AAV2 5' inverted terminal repeat (ITR), a liver-specific transcription regulatory region, a codon-optimized functionally active FVIII coding region, optionally one or more introns, a polyadenylation sequence, and an AAV2 3' ITR. In one example, 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), and 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 regions encodes the FVIII SQ variant. In another

example, the liver specific transcription regulatory region comprises a a1 micro-globulin enhancer sequence and the 186 base human alpha anti-trypsin (AAT) proximal promoter.

[0024] In one example, the AAV vector of the disclosure comprises Construct 100ATG comprising the nucleic acid sequence forth in SEQ ID NO: 9.

[0025] In one example, the AAV vector of the disclosure comprises Construct 100ATG bGH poly A comprising the nucleic acid sequence set forth in SEQ ID NO: 10.

[0026] In one example, the AAV vector of the disclosure comprises Construct 100ATG short bGH polyA sequence set forth in SEQ ID NO: 11.

[0027] In one example, the AAV vector of the disclosure comprises Construct 103ATG comprising the nucleic acid sequence forth in SEQ ID NO: 12.

[0028] In one example, the AAV vector of the disclosure comprises Construct 103ATG short bGH poly A comprising the nucleic acid sequence set forth in SEQ ID NO: 13.

[0029] In one example, the AAV vector of the disclosure comprises Construct 105ATG bGH poly A comprising the nucleic acid sequence set forth in SEQ ID NO: 14.

[0030] In one example, the AAV vector of the disclosure comprises Construct DC172ATG FVIII comprising the nucleic acid sequence set forth in SEQ ID NO: 15.

[0031] In one example, the AAV vector of the disclosure comprises Construct DC172ATG FVIII hAAT comprising the nucleic acid sequence set forth in SEQ ID NO: 16.

[0032] In one example, the AAV vector of the disclosure comprises Construct DC172 2xHCR ATG FVIII comprising the nucleic acid sequence set forth in SEQ ID NO: 17.

[0033] In one example, the AAV vector of the disclosure comprises Construct DC172 2xHCR ATG FVIII hAAT comprising the nucleic acid sequence set forth in SEQ ID NO: 18.

[0034] In one example, the AAV vector of the disclosure comprises Construct 2x SerpinA hAAT ATG FVIII comprising the nucleic acid sequence set forth in SEQ ID NO: 19.

[0035] In one example, the AAV vector of the disclosure comprises Construct 2x SerpinA hAAT ATG FVIII 2x μ-globulin enhancer comprising the nucleic acid sequence set forth in SEQ ID NO: 20.

[0036] In one example, the AAV vector of the disclosure Construct 100ATG short polyA 2x μ-globulin enhancer comprising the nucleic acid sequence set forth in SEQ ID NO: 21.

[0037] In one example, the AAV vector of the disclosure comprises Construct Factor VIII-BMN001 comprising the nucleic acid sequence set forth in SEQ ID NO: 22.

[0038] In one example, the AAV vector of the disclosure comprises Construct Factor VIII-BMN002 sequence set forth in SEQ ID NO: 23.

[0039] In one example, the AAV vector of the disclosure comprises Construct 99 comprising the nucleic acid sequence set forth in SEQ ID NO: 24.

[0040] In one example, the AAV vector of the disclosure comprises Construct 100 comprising the nucleic acid sequence set forth in SEQ ID NO: 25.

[0041] In one example, the AAV vector of the disclosure comprises Construct 100 reverse orientation comprising the nucleic acid sequence set forth in SEQ ID NO: 26.

[0042] In one example, the AAV vector of the disclosure Construct 100AT comprising the nucleic acid sequence set forth in SEQ ID NO: 27.

[0043] In one example, the AAV vector of the disclosure Construct 100AT 2x MG comprising the nucleic acid sequence set forth in SEQ ID NO: 28.

[0044] In one example, the AAV vector of the disclosure comprises Construct 100AT 2x MG bGH polyA comprising the nucleic acid sequence set forth in SEQ ID NO: 29.

[0045] In one example, the AAV vector of the disclosure comprises Construct 100AT 2x MG (reverse) bGH polyA comprising the nucleic acid sequence set forth in SEQ ID NO: 30.

[0046] In one example, the AAV vector of the disclosure comprises Construct 100 bGH polyA comprising the nucleic acid sequence set forth in SEQ ID NO: 31.

[0047] In one example, the AAV vector of the disclosure comprises Construct 100-400 comprising the nucleic acid sequence set forth in SEQ ID NO: 32.

[0048] In one example, the AAV vector of the disclosure comprises Construct 101 comprising the nucleic acid sequence set forth in SEQ ID NO: 33.

[0049] In one example, the AAV vector of the disclosure comprises Construct 102 sequence comprising the nucleic acid sequence set forth in SEQ ID NO: 34.

[0050] In one example, the AAV vector of the disclosure comprises Construct 103 comprising the nucleic acid sequence set forth in SEQ ID NO: 35.

[0051] In one example, the AAV vector of the disclosure comprises Construct 103 reverse orientation comprising the nucleic acid sequence set forth in SEQ ID NO: 36.

[0052] In one example, the AAV vector of the disclosure comprises Construct 103AT comprising the nucleic acid sequence set forth in SEQ ID NO: 37.

[0053] In one example, the AAV vector of the disclosure comprises Construct 103AT 2xMG comprising the nucleic acid sequence set forth in SEQ ID NO: 38.

[0054] In one example, the AAV vector of the disclosure comprises Construct 103AT 2xMG bGH polyA comprising the nucleic acid sequence set forth in SEQ ID NO: 39.

[0055] In one example, the AAV vector of the disclosure comprises the Construct 103 bGH polyA comprising the nucleic acid sequence set forth in SEQ ID NO: 40.

[0056] In one example, the AAV vector of the disclosure comprises Construct 104 comprising the nucleic acid comprising the nucleic acid sequence set forth in SEQ ID NO: 41.

[0057] In one example, the AAV vector of the disclosure comprises Construct 105 comprising the nucleic acid sequence set forth in SEQ ID NO: 42.

[0058] In one example, the AAV vector of the disclosure comprises Construct 106 comprising the nucleic acid sequence set forth in SEQ ID NO: 43.

[0059] In one example, the AAV vector of the disclosure comprises Construct 106AT comprising the nucleic acid sequence set forth in SEQ ID NO: 44.

[0060] In one example, the AAV vector of the disclosure comprises Construct 2x SerpinA hAAT comprising the nucleic acid sequence set forth in SEQ ID NO: 45.

[0061] In yet other examples, the present disclosure is directed to vector constructs encoding a functional Factor VIII polypeptide, wherein said 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 disclosure is also directed to the above described constructs in an opposite orientation.

[0062] The AAV vectors of the disclosure in single strand is less than about 7.0 kb in length, or is less than 6.5kb 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 ranges 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.

[0062a] In another aspect, there is provided a method of producing a recombinant adeno-associated virus (AAV) particle comprising A) culturing a cell that has been transfected with an AAV vector as described herein; and B) recovering recombinant AAV particle from the supernatant of the transfected cell.

[0063] In another example, the disclosure provides for methods of producing a recombinant adeno-associated virus (AAV) particle 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 and recovering recombinant AAV from the supernatant of the transfected cell.

[0064] The cells of the disclosure are any cell type are 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, NS0, SP2/0, PER.C6, Vero, RD, BHK, HT 1080, A549, Cos-7, ARPE-19 and MRC-5 cells, and including mammalian cells such as HEK293, HeLa, CHO, NS0, SP2/0, PER.C6, Vero, RD, BHK, HT 1080, A549, Cos-7, ARPE-19 and MRC-5 cells.

[0064a] In yet another aspect, there is provided a viral particle comprising the viral vector as described herein.

[0064b] In yet another aspect, there is provided a cell comprising the viral vector as described herein.

[0065] The disclosure also provides for a viral particle comprising any of the AAV vectors of the invention or any viral particle produced by the forgoing methods of the invention.

[0066] 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.

[0067] The invention also provides for cells comprising any of the AAV vectors of the invention, and viral particles produced by these cells of the invention.

[0068] In another example, the disclosure provides for methods of treating a patient suffering from hemophilia A comprising administering to the patient an effective amount of any of the AAV vectors of the disclosure, or a viral particle of the invention or a viral particles produced by a method of the disclosure.

[0068a] In yet another aspect, there is provided use of an AAV vector as described herein for preparation of a medicament for treatment of hemophilia A.

[0069] In a further example, the disclosure provides for a use of any of the AAV vectors of the disclosure for preparation of a medicament for the treatment of hemophilia A. In one example, the medicament comprises an amount of AAV vector that expresses human FVIII in an amount effective to treat hemophilia A.

[0069a] In yet another aspect, there is provided a composition comprising an AAV vector as described herein for use in the treatment of hemophilia A.

[0070] In another example, the disclosure provides for a composition comprising any of the AAV vectors of the disclosure for the treatment of hemophilia A. In one example, the composition comprises an amount of AAV vector that expresses human FVIII in an amount effective to treat hemophilia A.

[0071] In another example, the AAV vectors of the invention are used to produce AAV viral particles that are useful to treat a patient suffering from Hemophilia A.

DESCRIPTION OF DRAWINGS

[0072] Figure 1 provides a schematic of the UCL SQ vector. From left to right, the UCL SQ vector comprises the AAV2 5' ITR, wild-type AAV2 viral sequence, the 34 base human ApoE/C1 enhancer, the 32 base human AAT promoter distal X region, the 186 base human AAT promoter, including 42 bases of 5' UTR sequence, the codon-optimized human FVIII SQ sequence (see Nathwani et al., US Pat. App. Pub. No. 2013/0024960A1, published January 24,

2013, which is incorporated herein by reference in its entirety, and McIntosh et al., Blood 121:3335-3344, 2013), the 49 bases synthetic polyadenylation sequence, wild-type AAV2 viral sequence, and the AAV2 3'ITR. The UCL SQ vector is 5081 bases in length.

[0073] Figure 2 provides schematics and sequences of the Proto 1, Proto 1S, Proto 2S and Proto 3S vectors. (A) Schematic of the Proto 1 vector. Starting from the UCL SQ vector (see Figure 1), the extraneous wild-type AAV2 viral sequences were deleted, and sequences corresponding to restriction sites between the human AAT 5' UTR and the human FVIII coding region, and between the human FVIII termination codon and the synthetic polyadenylation sequence, were removed. (B) Schematic of the Proto 1S vector. Starting from the Proto 1 vector, 10 bases at the 3' end of the AAV2 5'ITR and 10 bases at the 5' end of the 3' ITR were deleted. (C) Schematic of the Proto 2S vector. Starting from the Proto 1S vector, the human ApoE/C1 enhancer and human AAT promoter distal X region were moved into a 100 base synthetic intron that was inserted between exons 1 and 2 of the human FVIII sequence. As indicated by the arrows, the orientation of the human ApoE/C1 enhancer and human AAT promoter distal X region are reversed compared to their orientation in Proto 1S. (D) Schematic of the Proto 3S vector. Starting from Proto 2S, the human AAT promoter distal X region is replaced by a second copy of the human ApoE/C1 enhancer in the reverse orientation.

[0074] Figure 3 provides schematics of the Proto 4, Proto 5, Proto 6 and Proto 7 vectors. (A) Schematic of the Proto 4 vector. Starting from the Proto 1 vector, the SQ sequence and a3 domain were deleted. (B) Schematic of the Proto 5 vector. Starting from the Proto 4 vector, a 129 base FVIII intron was inserted between exons 1 and 2 of the human Factor VIII sequence. (C) Schematic of the Proto 6 vector. Starting from the Proto 5 vector, a second copy of the human ApoE/C1 enhancer was inserted in the forward orientation into the FVIII intron. (D) Schematic of the Proto 7 vector. Starting from the Proto 5 vector, a second copy of the human ApoE/C1 enhancer was inserted in the reverse orientation into the FVIII intron.

[0075] Figure 4A – Figure 4KK provides schematics of the AAV FVIII vectors with improved promoter/enhancer sequences. (A) Schematic of Construct 100ATG. (B) Schematic of Construct 100ATG bGH polyA. (C) Schematic of Construct 100ATG short bGH poly A. (D) Schematic of Construct 103ATG. (E) Schematic of Construct 103ATG short bGH poly A. (F) Schematic of Construct 105ATG bGH polyA. (G) Schematic of Construct DC172ATG FVIII. (H) Schematic of Construct DC172ATG FVIII hAAT. (I) Schematic of Construct DC172 2xHCR ATG FVIII. (J) Schematic of Construct DC172 2xHCR ATG FVIII hAAT. (K) Schematic of Construct 2x SerpinA hAAT ATG FVIII. (L) Schematic of Construct 2x SerpinA hAAT ATG FVIII 2x μ-globulin enhancer. (M) Schematic of Construct 100ATG short bGH poly A 2x μ-

globulin enhancer. (N) Schematic of Construct Factor VIII-BMN001. (O) Schematic of Construct FVIII-BMN002. (P) Schematic of Construct 99. (Q) Schematic of Construct 100. (R) Schematic of Construct 100 reverse orientation. (S) Schematic of Construct 100AT. (T) Schematic of Construct 100AT 2x MG. (U) Schematic of Construct 100AT 2x MG bGH polyA. (V) Schematic of Construct 100AT 2x MG (reverse) bGH poly A. (W) Construct 100 bGH poly A. (X) Schematic of Construct 100-400. (Y) Schematic of Construct 101. (Z) Schematic of Construct 102. (AA) Schematic of Construct 103. (BB) Schematic of Construct 103 reverse orientation (CC) Schematic of Construct 103AT. (DD) Schematic of Construct 103AT 2x MG. (EE) Schematic of Construct 103AT 2x MG bGH poly A. (FF) Schematic of 103 sbGH poly A. (GG) Schematic of Construct 104. (HH) Schematic of Construct 105. (II) Schematic of Construct 106. (JJ) Schematic of Construct 106AT. (KK) Schematic of Construct 2x SerpinA hAAT.

[0076] Figure 5 provides the results of the evaluation of the Proto Constructs in Rag2 mice, and demonstrates Proto 1 transduces FVIII similarly to wild type.

[0077] Figures 6 and 7 demonstrate that Proto 1, Proto 1S, Proto 2S and Proto 3S express the VP1, VP2 and VP3 protein (Figure 5) and the VP1, VP2 and VP3 DNA (Figure 6).

[0078] Figures 8-10 demonstrate that improved promoter constructs have increased expression of FVIII.

DETAILED DESCRIPTION

[0079] Oversized AAV vectors are randomly truncated at the 5' ends and lack a 5' AAV ITR. Because AAV is a single-stranded DNA virus, and packages either the sense or antisense strand, the sense strand in oversized AAV vectors lacks the 5' AAV ITR and possibly portions of the 5' end of the target protein-coding gene, and the antisense strand in oversized AAV vectors lacks the 3' ITR and possibly portions of the 3' end of the target protein-coding gene. A functional transgene is produced in oversized AAV vector infected cells by annealing of the sense and antisense truncated genomes within the target cell.

[0080] The invention provides for AAV vectors encoding functionally active FVIII, i.e., completely packaged AAV FVIII vectors or AAV FVIII vectors with high expression activity. The AAV FVIII vectors of the invention have improved expression/particle, as well as improved

AAV virus production yield and simplified purification. Introducing one or more introns into the FVIII protein-coding region enhances expression. Reconfiguring the number and positioning of enhancers also enhances expression.

UCL SQ Vector

[0081] The UCL SQ vector, which is described in detail in Nathwani et al., US Pat. App. Pub. No. 2013/0024960A1, published January 24, 2013, which is incorporated herein by reference in its entirety, and McIntosh et al., Blood 121:3335-3344, 2013, is an oversized, i.e., greater than 5.0 kb, AAV vector. As shown in Figure 1, the UCL SQ vector comprises, from left to right, the AAV serotype 2 (AAV2) 5' ITR, wild-type AAV2 viral sequence, the 34 base human apolipoprotein E (ApoE)/C1 enhancer, the 32 base human alpha anti-trypsin (AAT) promoter distal X region, the 186 base human AAT promoter, including 42 bases of 5' untranslated region (UTR) sequence, the codon-optimized human FVIII sequence in which the B domain is replaced with the 14 amino acid SQ sequence, the 49 bases synthetic polyadenylation sequence, wild-type AAV2 viral sequence, and the AAV2 3'ITR. The UCL SQ vector is 5081 bases in length.

[0082] As shown in Nathwani et al., US Pat. App. Pub. No. 2013/0024960A1, published January 24, 2013, and McIntosh et al., Blood 121:3335-3344, 2013, the UCL SQ vector expresses functionally active FVIII in vitro and in vivo.

Proto 1, Proto 1S, Proto 2S and Proto 3S Vectors

[0083] To avoid the problem of over-sized AAV vectors and/or to increase the expression of the AAV vectors, the invention provides completely packaged, smaller, i.e., less than 5.0 kb, AAV vectors encoding the FVIII SQ variant. The 4970 bp nucleotide sequence of sequence of Proto 1 is set forth in SEQ ID NO: 1.

[0084] To generate the AAV vector Proto 1, sequences that appear to be unnecessary for production of functionally active FVIII were deleted as compared to the UCL SQ vector. As shown in Example 1, 110 bases of extraneous DNA were removed, including 53 bases of AAV2 viral sequence 3' to the AAV2 5'ITR, 46 bases of AAV2 viral sequence 5' to the AAV2 3'ITR, and 11 bases adjacent to the codon-optimized FVIII SQ coding region. The resultant Proto 1 vector is 4970 bases in length. When designed, it was unknown whether the Proto 1 vector would be capable of expressing functional FVIII polypeptide, either in vitro or in vivo.

[0085] To generate the AAV vector Proto 1S, 10 bases at the 3' end of the AAV2 5'ITR, and 10 bases at the 5' end of the AAV32 3'ITR, were removed from the Proto 1 vector. The resultant Proto 1S vector is 4950 bases in length. The nucleotide sequence of sequence of Proto 1S is set forth in SEQ ID NO: 2.

[0086] To generate the AAV vector Proto 2S, a synthetic 100 base intron was inserted between exons 1 and 2 of the codon-optimized FVIII SQ sequence in the Proto 1S vector. The 34 bases ApoE/C1 enhancer and 32 base human AAT promoter distal X region was removed from upstream of the human AAT promoter and inserted into the synthetic intron in the reverse orientation (as compared to the orientation when these elements are located upstream of the human AAT promoter). The resultant Proto 2S vector is 4983 bases in length. The nucleotide sequence of sequence of Proto 2S is set forth in SEQ ID NO: 3.

[0087] To generate the AAV vector Proto 3S, the human AAT promoter distal X region was removed from the Proto 2S vector, and replaced with a second copy of the 34 bases ApoE/C1 enhancer in the reverse orientation. The resultant Proto 3S vector is 4984 bases in length. The nucleotide sequence of sequence of Proto 3S is set forth in SEQ ID NO: 4.

Proto 4, Proto S, Proto 6 and Proto 7 Vectors

[0088] To reduce the size of AAV vectors and/or increase the expression of the AAV vectors, the invention also provides completely packaged, smaller, i.e., less than 5.0 kb, AAV vectors encoding B domain and a3 domain deleted FVIII.

[0089] To generate the AAV vector Proto 4, the 14 amino acid SQ sequence and the a3 domain located adjacent to the C domain was removed from the Proto 1 vector. The total amount of FVIII sequence deleted is 55 amino acids or 165 bases. The resultant Proto 4 vector is 4805 bases in length. The nucleotide sequence of sequence of Proto 4 is set forth in SEQ ID NO: 5.

[0090] To generate the AAV vector Proto 5, a 129 base truncated FVIII intron was inserted between exons 1 and 2 of the codon-optimized FVIII sequence in the Proto 4 vector. The resultant Proto 5 vector is 4934 bases in length. The nucleotide sequence of sequence of Proto 5 is set forth in SEQ ID NO: 6.

[0091] To generate the AAV Proto 6 vector, 34 bases of the FVIII intron were replaced with a second copy of the 34 base human ApoE/C1 enhancer in the forward orientation in the Proto 5 vector. The resultant Proto 6 vector is 4934 bases in length. The nucleotide sequence of sequence of Proto 6 is set forth in SEQ ID NO: 7.

[0092] To generate the AAV Proto 7 vector, 34 bases of the FVIII intron were replaced with a second copy of the 34 base human ApoE/C1 enhancer in the reverse orientation in the Proto 5 vector. The resultant Proto 7 vector is 4934 bases in length. The nucleotide sequence of sequence of Proto 7 is set forth in SEQ ID NO: 8.

[0093]

Additional AAV FVIII Vectors With Improved Promoter/Enhancer Sequences

[0094] Oversized AAV vectors with strong promoters were generated to increase expression of B domain and a3 domain deleted FVIII, and these constructs were generated with modified enhancer and/or promoter sequences. In some embodiments, the AAV FVIII vectors express a truncated functional FVIII. These constructs comprised one or more promoter and enhancer sequences such as ApoE HCR or fragments thereof, the μ-globulin enhancer or fragments thereof, the human alpha 1 antitrypsin promoter (hAAT) or fragments thereof, Serpin A enhancer or fragments thereof, the LP1 promoter enhancer or fragments thereof or macroglobulin enhancer or fragment thereof. These constructs comprise a polyadenylation sequence such as the bGH poly A sequence or the synthetic rabbit β-globin poly A sequence. In some embodiment, the constructs comprise an intron or fragments of an intron such as a hAAT intron or a human β-globin intron.

[0095] Construct 100ATG is 5511 bases in length. This construct is set forth in SEQ ID NO: 9 in which bases 1-145 are the 5'AAV2 ITR, bases 160-502 are an ApoE HCR, bases 509-726 are a hAAT promoter, bases 727-910 are a modified human β-globin 2nd intron, bases 923-5296 are a codon optimized SQ FVIII, bases 5305-5352 are a synthetic rabbit β-globin poly A and bases 5367-5511 are the 3' AAV2 ITR.

[0096] Construct 100ATG bGH poly A is 5688 bases in length. This construct is set forth in SEQ ID NO: 10 in which bases 1-145 are the 5' AAV2 ITR, bases 160-502 are an ApoE HCR, bases 509-726 are a hAAT promoter, bases 727-910 are a modified human β-globin 2nd intron,

bases 923-5296 are a codon optimized SQ FVIII, bases 5305-5529 are a bGH poly A and bases 5544-5688 are the 3' AAV2 ITR.

[0097] Construct 100ATG short bGH poly A is 5613 bases in length. This construct is set forth in SEQ ID NO: 11 in which bases 1-145 are the 5' AAV2 ITR, bases 160-502 are an ApoE HCR, bases 509-726 are a hAAT promoter, bases 727-910 are a modified human β-globin 2nd intron, bases 923-5296 are a codon optimized SQ FVIII, bases 5305-5454 are a short bGH poly A and bases 5469-5613 are the 3' AAV2 ITR.

[0098] Construct 103ATG is 5362 bases in length. This construct is set forth in SEQ ID NO: 12 in which bases 1-145 are the 5' AAV2 ITR, bases 169-344 are four copies (4x) of a 44bp ApoE repeat, bases 360-577 are a hAAT promoter, bases 578-761 are a modified human β-globin 2^{nd} intron, bases 774-5147 are a codon optimized SQ FVIII, bases 5156-5203 are a synthetic rabbit β-globin poly A and bases 5218-5362 are the 3' AAV2 ITR.

[0099] Construct 103ATG short bGH poly A is 5464 bases in length. This construct is set forth in SEQ ID NO: 13 in which bases 1-145 are the 5' AAV2 ITR, bases 169-344 are four copies (4x) of a 44bp ApoE repeat, bases 360-577 are a hAAT promoter, bases 578-761 are a modified human β-globin 2^{nd} intron, bases 774-5147 are a codon optimized SQ FVIII, bases 5156-5305 are a bGH short poly A and bases 5320-5464 are the 3' AAV2 ITR.

[00100] Construct 105ATG bGH polyA is 6354 bases in length. This construct is set forth in SEQ ID NO: 14 in which bases 1-145 are the 5' AAV2 ITR, bases 173-512 are two copies (2x) of a 170 bp microglobulin enhancer, bases 519-736 are a hAAT promoter, bases 737-920 are a modified human β-globin 2^{nd} intron, bases 933-5306 are a codon optimized SQ FVIII, bases 5315-5539 are a bGH poly A, bases 5546-6195 are two copies (2x) of a 325 bp ApoE HCR and bases 6210-6354 are the 3' AAV2 ITR.

[00101] Construct DC172ATG FVIII is 6308 bases in length. This construct is set forth in SEQ ID NO: 15 in which bases 1-145 are the 5' AAV2 ITR, bases 160-449 are two copies (2x) of a 145 bp macroglobulin enhancer, bases 450-1347 are an 898 bp hAAT promoter, bases 1348-1531 are a modified human β-globin 2^{nd} intron, bases 1544-5917 are a codon optimized SQ FVIII, bases 5926-6149 are a bGH poly A and bases 6164-6308 are the 3' AAV2 ITR.

[00102] Construct DC172ATG FVIII hAAT is 5635 bases in length, This construct is set forth as SEQ ID NO: 16 in which bases 1-145 are the 5' AAV2 ITR, bases 160-449 are two copies (2x) of a 145 bp macroglobulin enhancer, bases 457-674 are a hAAT promoter, bases 675-858 are a modified human β-globin 2nd intron, bases 871-5244 are a codon optimized SQ FVIII, bases 5253-5476 are a bGH poly A and bases 5490-5635 are the 3' AAV2 ITR.

[00103] Construct DC172 2xHCR ATG FVIII is 6962 bases in length. This construct is set forth in SEQ ID NO: 17 in which bases 1-145 are the 5' AAV2 ITR, bases 160-807 are two copies (2x) of a 321 bp ApoE HCR, bases 814-1103 are two copies (2x) of a 145 bp macroglobulin enhancer, bases 1104-2001 are a 898 bp hAAT promoter, bases 2002-2185 are a modified human β -globin 2nd intron, bases 2198-6571 are a codon optimized SQ FVIII, bases 6580-6803 are a bGH poly A and bases 6818-6962 are the 3' AAV2 ITR.

[00104] Construct DC172 2xHCR ATG FVIII hAAT is 6289 bases in length. This construct is set forth in SEQ ID NO: 18 in which bases 1-145 are the 5' AAV2 ITR, bases 160-807 are two copies (2x) of a 321 bp ApoE HCR, bases 814-1103 are two copies (2x) of a 145 bp macroglobulin enhancer, bases 1111-1328 are a hAAT promoter, bases 1329-1512 are a modified human β -globin 2nd intron, bases 1525-5898 are a codon optimized SQ FVIII, bases 5907-6130 are a bGH poly A and bases 6245-6289 are the 3' AAV2 ITR.

[00105] Construct 2x SerpinA hAAT ATG FVIII is 5430 bases in length. This construct is set forth in SEQ ID NO: 19 in which bases 1-145 are the 5' AAV2 ITR, bases 168-309 are two copies (2x) of a 71 bp SerpinA enhancer, bases 326-543 are a hAAT promoter, bases 544-727 are a modified human β-globin 2nd intron, bases 740-5113 are a codon optimized SQ FVIII, bases 5122-5271 are a short bGH poly A, and bases 5286-5430 are the 3'AAV2 ITR.

[00106] Construct 2x SerpinA hAAT ATG FVIII 2x μ-globulin enhancer is 5779 bases in length. This construct is set forth in SEQ ID NO: 20 in which bases 1-145 are the 5' AAV2 ITR, bases 168-309 are two copies (2x) of a 71 bp SerpinA enhancer, bases 326-543 are a hAAT promoter, bases 544-727 are a modified human β -globin 2nd intron, bases 740-5113 are a codon optimized SQ FVIII, bases 5122-5271 are a short bGH poly A, bases 5279-5618 are two copies (2x) of a 170 bp μ-globulin enhancer and bases 5635-5779 are the 3' AAV2 ITR.

[00107] Construct 100ATG short bGH poly A 2x μ-globulin enhancer is 5962 bases in length. This construct is set forth in SEQ ID NO: 21 in which bases 1-145 are the 5' AAV2 ITR, bases

160-502 are an ApoE HCR, bases 509-726 are a hAAT promoter, bases 727-910 are a modified human β-globin 2nd intron, bases 923-5296 are a codon optimized SQ FVIII, bases 5305-5454 are a short bGH poly A, bases 5462-5801 are two copies (2x) of a 170 bp microglobulin enhancer and bases 5818-5962 are the 3' AAV2 ITR.

[00108] Construct Factor VIII-BMN001 is 5919 bases in length. This construct is set forth in SEQ ID NO: 22 in which bases 1-145 are the 5' AAV2 ITR, bases 160-480 are an ApoE HCR, bases 487-884 are a 398bp hAAT promoter, bases 885-1145 are a truncated hAAT intron, bases 1155-5528 are a codon optimized SQ FVIII, bases 5537-5760 are a bGH poly A and bases 5775-5919 are the 3' AAV2 ITR.

[00109] Construct FVIII-BMN002 is 5306 bases in length. This construct is set forth in SEQ ID NO: 23 in which bases 1-145 are the 5' AAV2 ITR, bases 175-705 are an LP1 promoter/enhancer, bases 718-5091 are a codon optimized SQ FVIII, bases 5100-5147 are a synthetic rabbit β-globin poly A and bases 5162-5306 are the 3' AAV2 ITR.

[00110] Construct 99 is 5461 bases in length. This construct is set forth in SEQ ID NO: 24 in which bases 1-145 are the 5' AAV2 ITR, bases 169-627 are an ApoE HCR/MAR, bases 634-866 are a hAAT promoter, bases 873-5246 are a codon optimized SQ FVIII, bases 5255-5302 are a synthetic rabbit β-globin poly A and bases 5317-5461 are the 3' AAV2 ITR.

[00111] Construct 100 is 5327 bases in length. This construct is set forth in SEQ ID NO: 25 in which bases 1-145 are the 5' AAV2 ITR, bases 169-493 are an ApoE HCR, bases 509-726 are a hAAT promoter, bases 739-5112 are a codon optimized SQ FVIII, bases 5121-5168 are a synthetic rabbit β-globin poly A and bases 5183-5327 are the 3' AAV2 ITR.

[00112] Construct 100 reverse orientation is 5309 bases in length. This construct is set forth in SEQ ID NO: 26 in which bases 1-145 are the 5' AAV2 ITR, bases 160-484 are an ApoE HCR in reverse orientation, bases 491-708 are a hAAT promoter, bases 721-5094 are a codon optimized SQ FVIII, bases 5103-5150 are a synthetic rabbit β-globin poly A and bases 5165-5309 are the 3' AAV2 ITR.

[00113] Construct 100AT is 5532 bases in length. This construct is set forth in SEQ ID NO: 27 in which bases 1-145 are the 5' AAV2 ITR, bases 169-493 are an ApoE HCR, bases 509-726 are a hAAT promoter, bases 727-931 are a hAAT intron, bases 944-5317 are a codon optimized

SQ FVIII, bases 5326-5373 are a synthetic rabbit β-globin poly A and bases 5388-5532 are the 3' AAV2 ITR.

[00114] Construct 100AT 2x MG is 5877 bases in length. This construct is set forth in SEQ ID NO: 28 in which bases 1-145 are the 5' AAV2 ITR, bases 169-493 are an ApoE HCR, bases 508-847 are two copies (2x) of a 170 bp μ-globulin enhancer, bases 854-1071 are a hAAT promoter, bases 1072-1276 are a hAAT intron, bases 1289-5662 are a codon optimized SQ FVIII, bases 5671-5718 are a synthetic rabbit β-globin poly A and bases 5733-5877 are the 3' AAV2 ITR.

[00115] Construct 100AT 2x MG bGH poly A is 6054 bases in length. This construct is set forth in SEQ ID NO: 29 in which bases 1-145 are the 5' AAV2 ITR, bases 169-493 are an ApoE HCR, bases 508-847 are two copies (2x) of a 170 bp μ-globulin enhancer, bases 854-1071 are a hAAT promoter, bases 1072-1276 are a hAAT intron, bases 1289-5662 are a codon optimized SQ FVIII, bases 5671-5895 are a bGH poly A and bases 5910-6054 are the 3' AAV2 ITR.

[00116] Construct 100AT 2x MG (reverse) bGH poly A is 6054 bases in length. This construct is set forth in SEQ ID NO: 30 in which bases 1-145 are the 5' AAV2 ITR, bases 169-493 are an ApoE HCR, bases 508-847 are two copies (2x) of a 170 bp μ-globulin enhancer in reverse orientation, bases 854-1071 are a hAAT promoter, bases 1072-1276 are a hAAT intron, bases 1289-5662 are a codon optimized SQ FVIII, bases 5671-5895 are a bGH poly A and bases 5910-6054 are the 3' AAV2 ITR.

[00117] Construct 100 bGH poly A is 5504 bases in length. This construct is set forth in SEQ ID NO: 31 in which bases 1-145 are the 5' AAV2 ITR, bases 169-493 are an ApoE HCR, bases 509-726 are a hAAT promoter, bases 739-5112 are a codon optimized SQ FVIII, base pairs 5121-5345 are a bGH poly A and bases 5360-5504 are the 3' AAV2 ITR.

[00118] Construct 100-400 is 5507 bases in length. This construct is set forth in SEQ ID NO: 32 in which bases 1-145 are the 5' AAV2 ITR, bases 169-493 are an ApoE HCR, bases 512-906 are a 398 bp hAAT promoter, bases 919-5292 are a codon optimized SQ FVIII, bases 5301-5348 are a synthetic rabbit β-globin poly A and bases 5363-5507 are the 3' AAV2 ITR.

[00119] Construct 101 is 5311 base in length. This construct is set forth in SEQ ID NO: 33 in which bases 1-145 are the 5' AAV2 ITR, bases 170-477 are two copies (2x) of a 154bp ApoE

HCR, bases 493-710 are a hAAT promoter, bases 723-5096 are a codon optimized SQ FVIII, bases 5105-5152 are a synthetic rabbit β-globin poly A and bases 5167-5311 are the 3' AAV2 ITR.

[00120] Construct 102 is 5156 bases in length. This construct is set forth in SEQ ID NO: 34 in which bases 1-145 are the 5' AAV2 ITR, bases 169-322 are a 154bp ApoE HCR, bases 338-555 are a hAAT promoter, bases 568-4941 are a codon optimized SQ FVIII, bases 4950-4997 are a synthetic rabbit β-globin poly A and bases 5012-5156 are the 3' AAV2 ITR.

[00121] Construct 103 is 5178 bases in length. This construct is set forth in SEQ ID NO: 35 in which bases 1-145 are the 5' AAV2 ITR, bases 169-344 are four copies (4x) of a 44 bp ApoE HCR, bases 360-577 are a hAAT promoter, bases 590-4963 are a codon optimized SQ FVIII, bases 4972-5019 are a synthetic rabbit β-globin poly A and bases 5034-5178 are the 3' AAV2 ITR.

[00122] Construct 103 reverse orientation is 5160 bases in length. This construct is set forth in SEQ ID NO: 36 in which bases 1-145 are the 5' AAV2 ITR, bases 160-335are four copies (4x) of a 44 bp ApoE HCR in reverse orientation, bases 342-559are a hAAT promoter, bases 572-4945 are a codon optimized SQ FVIII, bases 4954-5001 are a synthetic rabbit β-globin poly A and bases 5016-5160 are the 3' AAV2 ITR.

[00123] Construct 103AT is 5383 bases in length. This construct is set forth in SEQ ID NO: 37 in which bases 1-145 are the 5' AAV2 ITR, bases 169-344 are four copies (4x) of a 44 bp ApoE HCR, bases 360-577 are a hAAT promoter, bases 578-782 are a hAAT intron, bases 795-4374 are a codon optimized SQ FVIII, bases 5177-5224 are a synthetic rabbit β-globin poly A and bases 5239-5383 are the 3' AAV2 ITR.

[00124] Construct 103AT 2x MG is 5728 bases in length. This construct is set forth in SEQ ID NO: 38 in which bases 1-145 are the 5' AAV2 ITR, bases 169-344 are four copies (4x) of a 44 bp ApoE HCR, bases 359-698 are two copies (2x) of a 170bp μ-globulin enhancer, bases 705-922 are a hAAT promoter, bases 923-1127 are a hAAT intron, bases 1140-5513 are a codon optimized SQ FVIII, bases 5522-5569 are a synthetic rabbit β-globin poly A and bases 5584-5728 are the 3' AAV2 ITR.

[00125] Construct 103AT 2x MG bGH poly A is 5905 bases in length. This construct is set forth in SEQ ID NO: 39 in which bases 1-145 are the 5' AAV2 ITR, bases 169-344 are four copies (4x) of a 44 bp ApoE HCR, bases 359-698 are two copies (2x) of a 170bp μ-globulin enhancer, bases 705-922 are a hAAT promoter, bases 923-1127 are a hAAT intron, bases 1140-5513 are a codon optimized SQ FVIII, bases 5522-5746 are a synthetic rabbit β-globin poly A and bases 5761-5905 are the 5' AAV2 ITR.

[00126] Construct 103 bGH poly A is 5355 bases in length. This construct is set forth in SEQ ID NO: 40 in which bases 1-145 are the 5' AAV2 ITR, bases 169-344 are four copies (4x) of a 44 bp ApoE HCR, bases 360-577 are a hAAT promoter, bases 590-4963 are a codon optimized SQ FVIII, bases 4972-5196 are a synthetic rabbit β-globin poly A and bases 5211-5355 are the 3' AAV2 ITR.

[00127] Construct 104 is 5618 bases in length. This construct is set forth in SEQ ID NO: 41 in which bases 1-145 are the 5' AAV2 ITR, bases 169-784 are four copies (4x) of a 154bp ApoE HCR, bases 800-1017 are a hAAT promoter, bases 1030-5403 are a codon optimized SQ FVIII, bases 5412-5459 are a synthetic rabbit β-globin poly A and bases 5474-5618 are the 3' AAV2 ITR.

[00128] Construct 105 is 5993 bases in length. This construct is set forth in SEQ ID NO: 42 in which bases 1-145 are the 5' AAV2 ITR, bases 173-512 are two copies (2x) of a 170 bp μ-globulin enhancer, bases 519-736 are a hAAT promoter, bases 749-5122 are a codon optimized SQ FVIII, bases 5131-5178 are a synthetic rabbit β-globin poly A, bases 5185-5834 are two copies (2x) of an ApoE HCR and bases 5849-5993 are the 3' AAV2 ITR.

[00129] Construct 106 is 5337 bases in length. This construct is set forth in SEQ ID NO: 43 in which bases 1-145 are the 5' AAV2 ITR, bases 173-512 are two copies (2x) of a 170 bp μ-globulin enhancer, bases 519-736 are a hAAT promoter, bases 749-5122 are a codon optimized SQ FVIII, bases 5131-5178 are a synthetic rabbit β-globin poly A and bases 5193-5337 are the 3' AAV2 ITR.

[00130] Construct 106AT is 5542 bases in length. This construct is set forth in SEQ ID NO: 44 in which bases 1-145 are the 5' AAV2 ITR, bases 173-512 are two copies (2x) of a 170 bp μ-globulin enhancer, bases 519-736 are a hAAT promoter, bases 737-941 are a hAAT intron, bases

954-5327 are a codon optimized SQ FVIII, bases 5336-5383 are a synthetic rabbit β-globin poly A and bases 5398-5542 are the 3' AAV2 ITR.

[00131] Construct 2x SerpinA hAAT is 5126 base. This construct is set forth in SEQ ID NO: 45 in which bases 1-145 are the 5' AAV2 ITR, bases 160-301 are an ApoE HCR, bases 308-525 are a hAAT promoter, bases 538-4911 are a codon optimized SQ FVIII, bases 4920-4967 are a synthetic rabbit β-globin poly A and bases 4982-5126 are the 3' AAV2 ITR.

AAV Vectors

[00132] 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, as shown below in Table 1. 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, for example, 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 such as those expressed in AAV 6. 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.

[00133] 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). 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.

[00134] 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.

[00135] 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 gene in accordance with the present invention encodes a Cap protein which is capable of packaging AAV vectors in the presence of rep and adeno helper function and is 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, for example the serotypes shown in Table 1.

Table 1. AAV serotypes

AAV Serotype	Genbank Accession No.
AAV-1	NC_002077.1
AAV-2	NC_001401.2
AAV-3	NC_001729.1
AAV-3B	AF028705.1
AAV-4	NC_001829.1
AAV-5	NC_006152.1
AAV-6	AF028704.1
AAV-7	NC_006260.1
AAV-8	NC_006261.1
AAV-9	AX753250.1
AAV-10	AY631965.1
AAV-11	AY631966.1
AAV-12	DQ813647.1
AAV-13	EU285562.1

[00136] 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, for example, GenBank Accession number U89790; GenBank Accession number J01901; GenBank Accession number AF043303; GenBank Accession number AF085716; Chlorini et al., J. Vir. 71: 6823-33(1997); Srivastava et al., J. Vir. 45:555-64 (1983); Chlorini et al., J. Vir. 73:1309-1319 (1999); Rutledge et al., J. Vir. 72:309-319 (1998); and Wu et al., J. Vir. 74: 8635-47 (2000).

[00137] 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.

[00138] 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. 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.

[00139] 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, for example, METHODS IN MOLECULAR BIOLOGY, ed. Richard, Humana Press, NJ (1995); O'Reilly et al., BACULOVIRUS EXPRESSION VECTORS, A LABORATORY MANUAL, Oxford Univ. Press (1994); Samulski et al., J. Vir. 63:3822-8 (1989); Kajigaya et al., Proc. Nat'l. Acad. Sci. USA 88: 4646-50 (1991); Ruffing et al., J. Vir. 66:6922-30 (1992); Kirnbauer et al., Vir. 219:37-44 (1996); Zhao et al., Vir. 272:382-93 (2000); and Samulski et al., 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.

[00140] 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).

[00141] 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); Lebacq-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

[00142] 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.

[00143] 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.

[00144] 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.

[00145] In some embodiments, the AAV cap genes are present in a plasmid. The plasmid can further comprise an AAV rep gene. 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.

[00146] 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.

[00147] 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

[00148] The viral particles comprising the AAV vectors of the invention may be redocued 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. Bombyxmori 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.

[00149] 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).

[00150] 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); Lebacq-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).

[00151] 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, NS0, SP2/0, PER.C6, Vero, RD, BHK, HT 1080, A549, Cos-7, ARPE-19 and MRC-5 cells.

Testing of AAV FVIII Vectors

[00152] Assays to test the completely packaged AAV FVIII vectors of the invention include, for example, (1) transient transfection of double-stranded DNA plasmids comprising the AAV vector nucleic acids in HepG2 cells, a cell line derived from human liver to check liver-specific mRNA expression and splicing, and FVIII protein production and secretion in vitro; (2) production of AAV virions comprising the AAV FVIII vectors in 293 cells and baculovirus-infected insect cells; (3) evaluation of the AAV vector nucleic acids by alkaline gel analysis and replication assays; and (4) evaluation of FVIII expression, FVIII activity, and FVIII specific activity in Rag2 mice. These assays are described in greater detail in the Examples.

[00153] The completely packaged AAV FVIII vectors of the invention display at least the same expression and/or activity as the UCL SQ vector, and preferably 1.5-fold, 2-fold, 3- fold, 4-fold, or 5-fold or more expression and/or activity as compared to the UCL SQ vector.

[00154] The completely packaged AAV FVIII vectors of the invention have high vector yield with little or no fragmentary genome contaminants, and preferably 1.5-fold, 2-fold, 3- fold, 4-fold, or 5-fold greater vector yield as compared to the UCL SQ vector.

[00155] Other aspects and advantages of the present invention will be understood upon consideration of the following illustrative examples.

EXAMPLES

Example 1
Generation of Proto 1, Proto 1S, Proto 2S and Proto 3S Vectors

[00156] The UCL SQ vector, which is described in detail in Nathwani et al., US Pat. App. Pub. No. 2013/0024960A1, published January 24, 2013, which is incorporated herein by reference in its entirety, and McIntosh et al., Blood 121:3335-3344, 2013, is an oversized, i.e., greater than 5.0 kb, AAV vector. As shown in Figure 1, the UCL SQ vector comprises, from left to right, the AAV serotype 2 (AAV2) 5' ITR, wild-type AAV2 viral sequence, the 34 base human apolipoprotein E (ApoE)/C1 enhancer, the 32 base human alpha anti-trypsin (AAT) promoter distal X region, the 186 base human AAT promoter, including 42 bases of 5' untranslated region (UTR) sequence, the codon-optimized human FVIII sequence in which the B domain is replaced with the 14 amino acid SQ sequence, the 49 bases synthetic polyadenylation

sequence, wild-type AAV2 viral sequence, and the AAV2 3'ITR. The UCL SQ vector is 5081 bases in length.

[00157] To obtain a vector that is smaller than the UCL SQ vector, DNA sequences believed by the inventors herein to be unnecessary for FVIII expression and/or activity, or for AAV virion production, were removed from the UCL SQ vector sequence. Extraneous DNA sequence was removed, including 53 bases of AAV2 viral sequence 3' to the AAV2 5'ITR, 46 bases of AAV2 viral sequence 5' to the AAV2 3'ITR, and 11 bases adjacent to the codon-optimized FVIII SQ coding region. The resultant Proto 1 vector, which is 4970 bases in length, is shown in schematic form in Figure 2A, and the sequence is set forth in SEQ ID NO: 1. Proto 1 produced infectious virus and encodes a functional Factor VIII polypeptide.

[00158] Sequences adjacent to the hairpin loop in the AAV2 ITR may also be dispensable in recombinant AAV vectors (see Srivastava et al., US Pat. No. 6,521,225; Wang et al., J. Virol. 70:1668-1677, 1996; and Wang et al., J. Virol. 71:3077-3082, 1997). To further reduce the size of the Proto 1 vector, 10 bases of AAV2 sequence was removed directly 3' to the hairpin loop in the AAV2 5'ITR and 10 bases of AAV2 sequence was removed directly 5' to the hairpin loop in the AAV2 3'ITR. The resultant Proto 1S vector, which is 4950 bases in length, is shown in schematic form in Figure 2B, and the sequence is set forth in SEQ ID NO: 2.

[00159] In an effort to increase the expression of the FVIII SQ variant in the Proto 1S vector, a 100 base synthetic intron was inserted between exons 1 and 2 in the codon-optimized FVIII sequence. It is known that insertion of an intron can result in increased level of mRNA expression in otherwise intron-less genes, such as, for example, the interferon genes.

[00160] Enhancers are defined as working in a distance- and orientation-independent manner. The 34 base ApoE/C1 enhancer works in a distance- and orientation-independent manner with respect to FVIII expression, as exemplified by its presumptive enhancer activity in Gray et al., US Pat. No. 8,030,065 (FIX expression) and in Nathwani et al., US Pat. App. Pub. No. 2013/0024960 (FVIII expression), both of which are incorporated herein by reference in their entirety. The 32 base human AAT promoter distal X region, described in Di Simone et al., EMBO J. 6:2759-2766, 1987, is located within a regulatory domain that enhances expression of a heterologous promoter.

[00161] In another attempt to further increase the expression of the FVIII SQ variant in the Proto 1S vector, the synthetic intron sequence incorporated the 34 base human ApoE/C1 enhancer and 32 base human AAT promoter distal X region, which was moved from its location upstream of the human AAT promoter. These two regulatory elements were inserted in the reverse orientation with respect to their orientation in Proto 1S. The resultant Proto 2S vector, which is 4983 bases in length, is shown in schematic form in Figure 2C, and the sequence set forth in SEQ ID NO: 3.

[00162] As the human AAT promoter distal X region had not previously been shown to function downstream from the transcriptional start site in an intron, this regulatory element in the Proto 2S vector was replaced with a second copy of the 34 base human ApoE/C1 enhancer in the same orientation as the first copy of the enhancer in the intron. The resultant Proto 3S vector, which is 4985 bases in length, is shown in schematic form in Figure 2D, and the sequence is set forth in SEQ ID NO: 4.

[00163] The Proto 1, Proto 1S, Proto 2S and Proto 3S vector nucleic acids were cloned into the pUC19 bacterial expression plasmid, thereby generating double-stranded forms of the AAV FVIII vectors.

Example 2

Generation of Proto 4, Proto 5, Proto 6 and Proto 7 Vectors

[00164] To further reduce the size of the Proto 1 vector and/or increase the expression of FVIII as compared to the Proto 1 vector, the a3 domain, which is located adjacent to the light chain or C domain, was deleted. The a3 domain is involved in binding to von Willenbrand Factor, but may be dispensable for functionally active FVIII in vivo.

[00165] Starting from the Proto 1 vector, the 14 amino acid SQ sequence and 41 amino acids a3 domain (corresponding to amino acids 1649-1689 of wild-type FVIII) were deleted. The resultant Proto 4 vector, which is 4805 bases in length, is shown in schematic form in Figure 3A, and the sequence is set forth in SEQ ID NO: 5.

[00166] In an attempt to increase the expression of the B domain and a3 domain deleted FVIII, a 129 base, truncated FVIII intron was inserted between exons 1 and 2 in the codon-optimized FVIII sequence in the Proto 4 vector. The resultant Proto 5 vector, which is 4934

bases in length, is shown in schematic form in Figure 3B, and the sequence is set forth in SEQ ID NO: 6.

[00167] In an attempt to further increase the expression of the B domain and a3 domain deleted FVIII, a second copy of the 34 base human ApoE/C1 enhancer was inserted in either the forward or reverse orientation in the Proto 5 vector. The resultant Proto 6 vector, which is 4934 bases in length and has the intronic ApoE/C1 enhancer in the forward orientation, is shown in schematic form in Figure 3C, and the sequence is set forth in SEQ ID NO: 7.

[00168] The resultant Proto 7 vector, which is 4934 bases in length and has the intronic ApoE/C1 enhancer in the reverse orientation, is shown in schematic form in Figure 3D, and the sequence is set forth in SEQ ID NO: 8.

[00169] The Proto 4, Proto 5, Proto 6 and Proto 7 vector nucleic acids were cloned into the pUC19 bacterial expression plasmid, thereby generating double-stranded forms of the AAV FVIII vectors.

Example 3
Assays to Test the Expression and Activity of AAV FVIII Vectors

[00170] Assays to test the AAV FVIII vectors of the invention include, for example, (1) transient transfection of double-stranded DNA plasmids comprising the AAV vector nucleic acids in HepG2 cells, a cell line derived from human liver to check liver-specific mRNA expression and splicing, and FVIII protein production and secretion in vitro; (2) production of AAV virions comprising the AAV FVIII vectors in 293 cells and baculovirus-infected insect cells; (3) evaluation of the AAV vector nucleic acids by alkaline gel analysis and replication assays; and (4) evaluation of FVIII expression, FVIII activity, and FVIII specific activity in Rag2 mice.

Transient Transfection Assays.

[00171] A preliminary in vitro assay is performed to compare the FVIII expression and activity from the AAV FVIII vectors of the present invention with that from the UCL SQ vector. Double-stranded forms of the AAV FVIII vectors of the present invention are transiently transfected into the human liver cell line, HepG2. After transfection, for example, 24 or 48 hours later, FVIII antigen and activity in the culture supernatants is measured.

[00172] Using this assay, the FVIII activity in HepG2 cells transiently transfected with the Proto 1, Proto 1S and Proto 2S vectors was similar to the FVIII activity obtained using the UCL SQ vector, demonstrating that the Proto 1, Proto 1S and Proto 2S vectors were capable of expressing functional Factor VIII protein.

Production of AAV Virions in 293 cells and Baculovirus-Infected Insect Cells.

[00173] To demonstrate that the AAV FVIII vectors of the present invention indeed package the nucleic acids encoding FVIII, the double-stranded forms of the AAV FVIII vectors generated as described in Examples 1 and 2 are introduced into cells capable of producing AAV virions. In a first AAV virus production system, plasmids comprising the AAV FVIII vector nucleic acids in double-stranded form are co-transfected into 293 cells together with a plasmid that expresses the AAV Cap and Rep proteins and a plasmid that expresses Adenovirus helper functions needed to for AAV virion production. In a second AAV virus production system, baculovirus constructs are generated expressing the AAV FVIII vector nucleic acids and the AAV Cap and Rep proteins, and then are co-infected into insect Sf9 cells. The resultant AAV virions produced in the transiently transfected 293 cells or baculovirus-infected Sf9 cells are purified and analyzed by standard methods known in the art.

Evaluation by Alkaline Gel and Replication Assay

[00174] An alkaline gel electrophoresis assay is used to determine the size of the packaged nucleic acid. A replication center assay is used to determine which AAV FVIII vectors are packaged in an intact form by both packaging methods.

[00175] A primer extension assay is used to quantify the amount of AAV FVIII vectors nucleic acids that have complete ends, i.e., terminate at the 5‘ end of the hairpin loop in the AAV2 5’ITR (sense strand) or 3’ITR (anti-sense strand).

[00176] Alternatively, a PCR assay is used to determine whether the AAV FVIII vectors nucleic acids have complete ends, i.e., terminate at the 5‘ end of the hairpin loop in the AAV2 5’ITR (sense strand) or 3’ITR (anti-sense strand).

Evaluation in Rag2 mice

[00177] The AAV virions produced in transiently transfected 293 cells or baculovirus-infected Sf9 cells packaged vectors are tested for FVIII expression and activity in Rag2 mice at 2e11,

2e12, and 2e13 viral genomes (vg)/kg, given intravenously. Rag2 mice are used in this assay because FVIII expression and/or activity is/are not complicated by the presence of a host immune response to the AAV virus or human FVIII protein.

[00178] FVIII antigen is determined using an ELISA-based assay. FVIII activity is determined using a FXa activation assay and/or a coagulation assay. Using the FVIII antigen and activity assays, the FVIII specific activity is determined.

[00179] Numerous modifications and variations in the practice of the invention are expected to occur to those skilled in the art upon consideration of the presently preferred embodiments thereof. Consequently, the only limitations which should be placed upon the scope of the invention are those which appear in the appended claims.

Example 4
Generation of Constructs with Improved Promoter/Enhancer Sequences

[00180] To generate additional AAV vectors with strong promoters that increase expression of functional FVIII, constructs were generated with modified enhancer and/or promoter sequences. In some embodiments, the constructs comprised shortened versions of the ApoE or the μ-globulin enhancers. These constructs were generated using standard DNA cloning techniques and the sequences thereof are are shown in SEQ IS NOS: 9-45.

Example 5
Generation of AAV Viral Particles

Generation of Recombinant Bacmid

[00181] DH10 Bac competent cells were thawed on ice. Recombinant shuttle plasmid (e.g., pFB-GFP) was added and gently mixed with the competent cells and incubated on ice for 30 minutes. The competent cells were then subjected to heat at a temperature of approximately 42°C for 30 seconds and then chilled on ice for 2 minutes. The competent cells were shocked with heat for 30 seconds at 42°C and chilled on ice for 2 min. SOC was added to the cells and allowed to incubate at 37°C with agitation for 4 hours to allow recombination to take place. During the incubation period, X-gal was spread onto two LB-plates (additionally containing various antibiotics (e.g., kanamycin, gentamycin and tetracycline) for transformation, is followed by IPTG.

[00182] An amount of the incubation mixture was obtained, diluted and then spread onto the two LB-plates and incubated at 37°C for approximately 30-48 hours. Several white colonies were selected from each plate and cultured overnight in LB medium containing the same combination of antibiotics provided in the LB-plates. Next, Bacmid DNA and a glycerol stock was prepared and stored at -80°C.

Purification of recombinant Bacmid DNA

[00183] An amount of the Bacmid glycerol stock is removed and inoculated in LB medium containing the same combination of antibiotic provided in the LB-plates described in Example 1. Cultures are allowed to grow overnight at 37°C with shaking. Next, an amount of the culture is spun in a microfuge at full speed for approximately 30 seconds.

[00184] The pellets were resuspended in a resuspension buffer using a pipette followed by a lysis buffer, and the tube was inverted several times to mix the buffer and then incubated at room temperature for approximately 5 minutes. An exemplary resuspension buffer comprises 50 mM Tris-CL, pH 8.0, 10 mM EDTA and 100ug/mL RNase A. An exemplary lysis buffer comprises 200 mM NaOH and 1% SDS. An amount of precipitate buffer (e.g., a buffer comprising 3.0 M potassium acetate, pH 5.5) was slowly added and the tube was inverted several times to mix the buffer and then incubated on ice for approximately 10 minutes. The tube was centrifuged for approximately 10 minutes at full speed and the supernatant is poured into a tube containing isopropanol. The tube was inverted several times to mix the solution.

[00185] Next, the solution was centrifuged at full speed for approximately 15 minutes at room temperature and the supernatant was removed immediately after centrifuge with pipette.

[00186] An amount of 70% ethanol was added to rinse the pellet and spun again at full speed for 1 minute. The ethanol was then removed and the solution is spun again to remove trace of the ethanol. An amount of TE/EB Buffer was added to each tube and the pellet is carefully dissolved by pipette. The solution was stored at –20°C if not used immediately.

Production of P0 stock of recombinant baculovirus

[00187] Sf9 cells were seeded at approximately 1 x 10^6 cells/well in a 6-well plate (or 6 x 10^6 cells in a 10-cm plate or 1.7 x 10^7 cells in a 15-cm dish) and the cells were allowed to attach for at least 1 hour before transfection.

[00188] Transfection solutions A and B are prepared as follows: Solution A: an amount of the Bacmid was diluted into an amount of serum free media without antibiotics in a 15-mL tube. Solution B: an amount of CellFectin was diluted into an amount of serum free media without antibiotics in a 15-mL tube. Solution B was added to Solution A and gently mixed by pipette approximately 3 times by pipette, and incubated at room temperature for 30 ~ 45 minutes. Next, medium from the plate was aspirated and an amount of serum free media without antibiotics was added to wash the cells. An amount of SF900II without antibiotics was added to each tube containing lipid-DNA mixtures.

[00189] The medium from the cells was aspirated, the transfection solution was added to the cells and the cells were incubated for approximately 5 hours at 28°C. The transfection solution was removed and an amount of and serum free media + antibiotics is added, and incubated for approximately 4 days at 28°C. Media that contains the recombinant baculovirus was collected and spun for approximately 5 minutes at 1000 rpm to remove cell debris. The baculovirus was stored at 4°C under dark.

Amplification of baculovirus (P1)

[00190] Sf9 cells were grown to approximately 4 x 10^6 cells/mL and diluted to approximately 2 x 10^6 cells/mL with fresh medium in shaking flasks. An amount of the Sf9 cells were infected with an amount of the P0 stock baculovirus. The multiplicity of infection (MOI) is approximately 0.1.

[00191] The Sf9 cells were incubated for approximately 3 days and the baculovirus was harvested. The cells were spun at 2,000 rpm for 5 minutes to pellet the cells and the supernatant was collected and stored at 4°C under dark. The titer of the baculovirus was determined according to Clontech's Rapid Titer Kit protocol.

Production of AAV using P1 recombinant baculoviruses

[00192] Sf9 cells were grown to about 1 x 10^7 cells/mL and diluted to about 5 x 10^6 cells/mL. An amount of the diluted Sf9 cells were infected with Bac-vector (5Moi) and Bac-helper (15Moi) for 3 days. Cell viability was assessed on the third day (approximately 50% ~ 70% dead cells are observed).

[00193] Cell pellets were harvested by centrifugation at 3000 rpm for 10 minutes. Media was removed and the cells lysed (or the cell pellets were stored at -20°C if not used immediately).

Lysis and banding protocol

[00194] An amount of Sf9 lysis buffer plus Benzonase is added to each cell pellet and vortexed thoroughly to resuspend the cells. The resuspended Sf9 cells were incubated on ice for approximately 10 min. to cool lysate. The lysate was sonicated for approximately 20 seconds to lyse the cells thoroughly and then incubated at 37°C for approximately 30 minutes.

[00195] An amount of 5M NaCl was added and the mixture is vortexed and then incubated for another 30 minutes at 37°C. An amount of NaCl was added to bring the salt concentration to about 500mM, vortexed and centrifuged at 8,000 rpm for 20 minutes at 15°C to produce a cleared lysate.

[00196] The cleared lysate proceeds to ultracentrifugation steps. A CsCl-gradient was prepared by adding the cleared lysate first, then an amount of 1.32g/cc and an amount of 1.55g/cc CsCl solutions through a syringe with long needle. The interface between the CsCl solutions was marked. PBS was added up to the top of the centrifuge tubes and the tubes are carefully balanced and sealed.

[00197] The tubes were centrifuged at 55,000 rpm for approximately 20 hours at 15°C. A hole was puncture on the top of each tube and the AAV band located slightly above the interface mark of the two CsCl solutions is marked.

[00198] A second CsCl centrifugation is conducted by transferring the AAV solution to centrifuge tube for 70.1 Ti rotor and an amount of CsCl solution to near top of the tube was added. The tubes were balanced and sealed. The tubes are centrifuged at 65,000rpm for approximately 20 hours and the AAV band (lower band, the higher band is empty capsids) was collected.

Example 5

Evaluation of the Constructs in Rag2 Mice

[00199] AAV genomes which comprise a codon optimized SQ FVIII-encoding gene sequence were generated using baculovirus and 293 cells using the UCL SQ, Proto 1, Proto S1, Proto S2

and Proto S3 constructs. The packaging limits are 4800bp for baculovirus and 4950 for 293 cells.

[00200] As shown in Figure 5, Proto 1 with truncated or non-truncated genomes transduce FVIII similar to the UCL SQ construct. The AAV5.2 produced from baculovirus and 293T cell lysates as measured on a on 4-12% Bis-Tris Gel. Each samples expressed VP1, VP2 and VP3 protein, as shown in the Figure 6. The genomic DNA from the AAV samples was run on 0.8% alkaline agarose gels, as shown in Figure 7.

[00201] Transduction of Proto 1 was similar to the UCL SQ construct when these AAV were made by the baculovirus system. The inclusion of the intron containing Proto2S and 3S did not transduce better than Proto 1. The UCL SQ vector containing the AAV flanking sequences made in 293 cells were more potent than the UCL SQ lacking the AAV sequence made in baculovirus. As a result, additional enhancers were added to Proto 1, e.g. Construct 101, 102, 102 and 104, in an attempt to increase potency.

Example 6
Expression and Activity of AAV FVIII Vectors with Improved Promoters/Enhancer Sequences

[00202] The expression and activity of AAV vectors comprising Constructs 99 to Construct 106 were tested using the hydrodynamic injection protocol. Hydrodynamic delivery is a rapid method to screen liver promoters in vivo. AAV plasmid DNA was generated using the method described in Example 5 and then diluted in TransIT-QR Hydrodynamic Delivery Solution. The plasmid DNA was injected into the tail vein of 5-6 week old C57Bl/6 mice (18-25 g) at a volume determined by (mouse weight (g)/10) = 0.1 ml delivery solution). The injection time was less than 5 seconds. Plasma from each mouse was collected 48 hours after injection and the amount of FVIII antigen expressed was measured using an ELISA assay.

[00203] Increasing doses of Proto 1 plasmid (2.5, 5, 12.5 and 50 μg) were injected into the tail vein of mice. The amount of FVIII in the plasma of the injected mouse was measured using an ELISA test and recombinant FVIII (Xyntha SQ equivalents) was used as a standard for comparison.

[00204] To investigate expression the improved promoter/enhancer elements of construct p100-400, Construct 100(p100), Construct FVIII-BMN001 (pFVIII-BMN001), Proto1, Construct 100AT (p100-AT), Construct 100 bGH poly A (p100-bGHPA), Construct 101 (p101)

and Construct 104 (p104). As shown in Figure 8, all constructs produced functional FVIII at varying levels of efficiency.

[00205] Figures 9 and 10 provide data for injection of 1 μg of plasmid of various constructs. As shown in Figure 8, injection of Construct FVIII-BMN001, Constuct FVIII-BMN002, Construct 102 (p102), Construct 103 (p103) and Construct 104 (p104) resulted in expression of at least 20 ng of FVIII in 5 out of 10 mice. As shown in Figure 9, injection of Construct FVIII-BMN001, Construct 103 (p103), Construct 103-AT (p103-AT; 398 bp hAAT promoter), Construct 100 (p100), Construct 100AT (p100-AT; 398 bp hAAT promoter) resulted in expression of at least 100 ng/ml of FVIII in 5 out of 10 mice.

What is claimed:

1. An adeno-associated virus (AAV) vector comprising an AAV2 5' inverted terminal repeat (ITR), a liver-specific transcription regulatory region, a functionally active FVIII coding region, a polyadenylation sequence, an AAV2 3' ITR, and optionally one or more introns, wherein said AAV vector is less than 5.0 kb in length, wherein the functionally active FVIII coding region comprises nucleotides 923-5296 of SEQ ID NO: 9.

2. The AAV vector of claim 1, wherein said liver-specific transcriptional regulatory region is located immediately 3' to said AAV2 5 ' ITR.

3. The AAV vector of claim 1 or 2, wherein said liver-specific regulatory region comprises nucleotides 146-397 of SEQ ID NO:1.

4. The AAV vector of any one of claims 1-3, which comprises nucleotides 1-397 of SEQ ID NO:1.

5. The AAV vector of any one of claims 1 – 4,
comprising the nucleotide sequence of SEQ ID NO: 1.,

6. The AAV vector of claim 1, comprising the nucleotide sequence set forth in SEQ ID NO: 2.

7. The AAV vector of claim 1, comprising the nucleotide sequence set forth in SEQ ID NO: 3.

8. The AAV vector of claim 1, comprising the nucleotide sequence set forth in SEQ ID NO: 4.

9. The AAV vector of claim 1, comprising the nucleotide sequence set forth in SEQ ID NO: 5.

10. The AAV vector of claim 1, comprising the nucleotide sequence set forth in SEQ ID NO: 6.

11. The AAV vector of claim 1, comprising the nucleotide sequence set forth in SEQ ID NO: 7.

12. The AAV vector of claim 1, comprising the nucleotide sequence set forth in SEQID NO: 8.

13. A method of producing a recombinant adeno-associated virus (AAV) particle comprising
A) culturing a cell that has been transfected with an AAV vector of any one of claim 1 - 12; and
B) recovering recombinant AAV particle from the supernatant of the transfected cell.

14. A viral particle comprising an AAV vector of any one of claims 1-12.

15. A cell comprising an AAV vector of any one of claims 1-12.

16. Use of an AAV vector of any one of claims 1-12 for preparation of a medicament for treatment of hemophilia A.

17. A composition comprising an AAV vector of any one of claims 1-12 for use in the treatment of hemophilia A.