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(54) Titre : NUCLEASES MODIFIEES UTILES POUR LE TRAITEMENT DE L'HEMOPHILIE A

(54) Title: ENGINEERED NUCLEASES USEFUL FOR TREATMENT OF HEMOPHILIA A

Fig. 1A

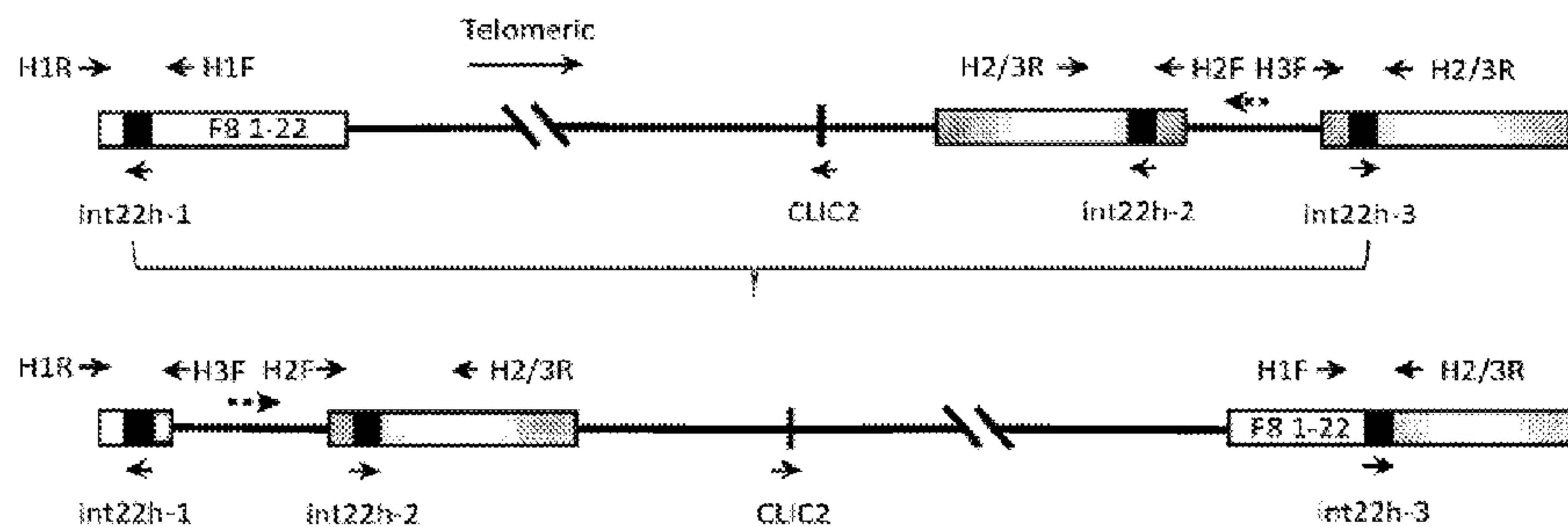
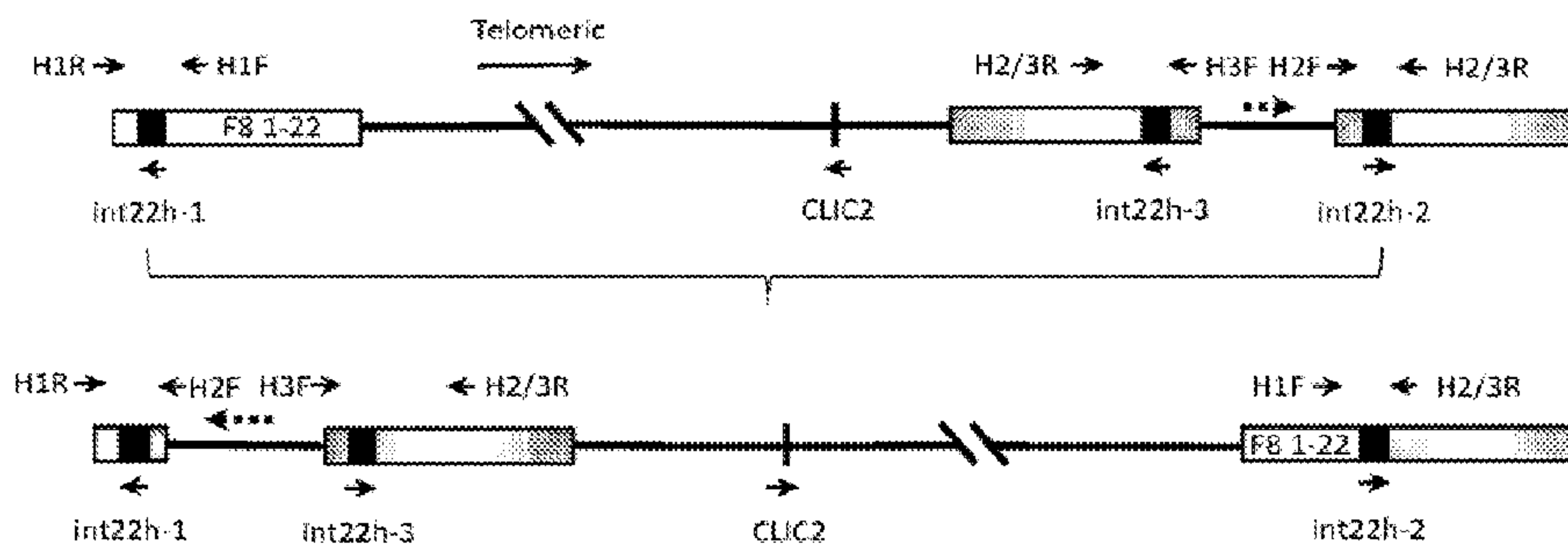


Fig. 1B



(57) **Abrégé/Abstract:**

The present invention encompasses engineered nucleases which recognize and cleave a recognition sequence within the int22h-1 sequence of a Factor VIII gene. The present invention also encompasses methods of using such engineered nucleases to make genetically-modified cells, and the use of such cells in a pharmaceutical composition and in methods for treating hemophilia A. Further, the invention encompasses pharmaceutical compositions comprising engineered nuclease proteins, nucleic acids encoding engineered nucleases, or genetically -modified cells of the invention, and the use of such compositions for treating of hemophilia A.

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Fig. 1A

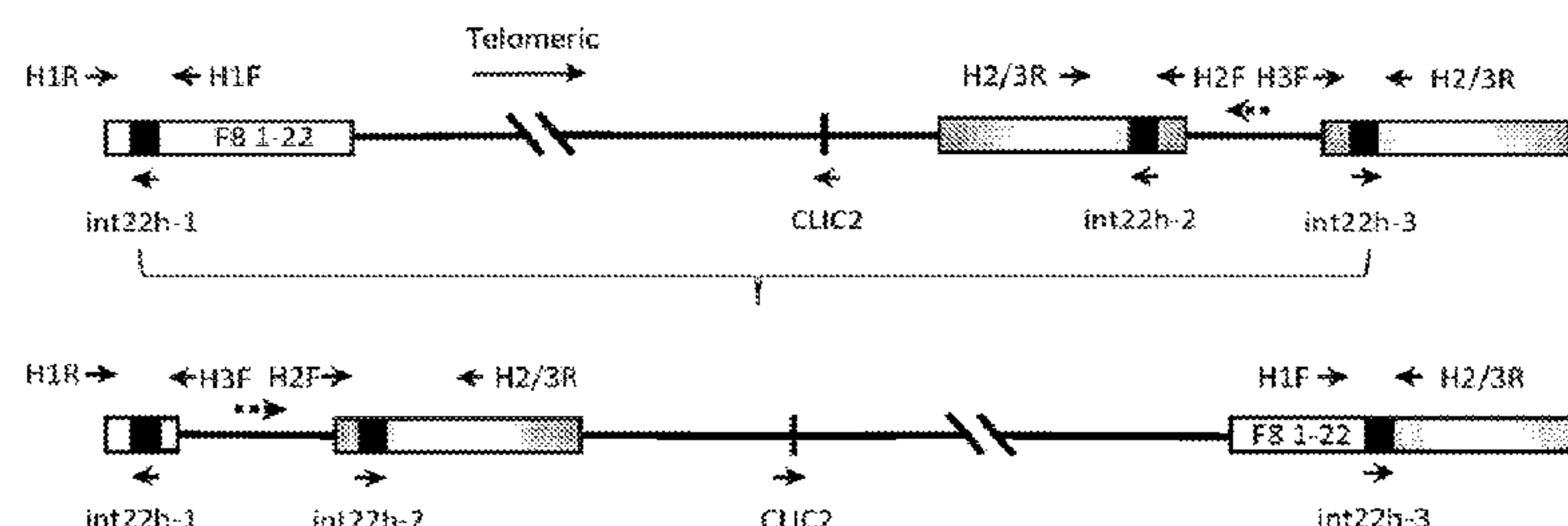
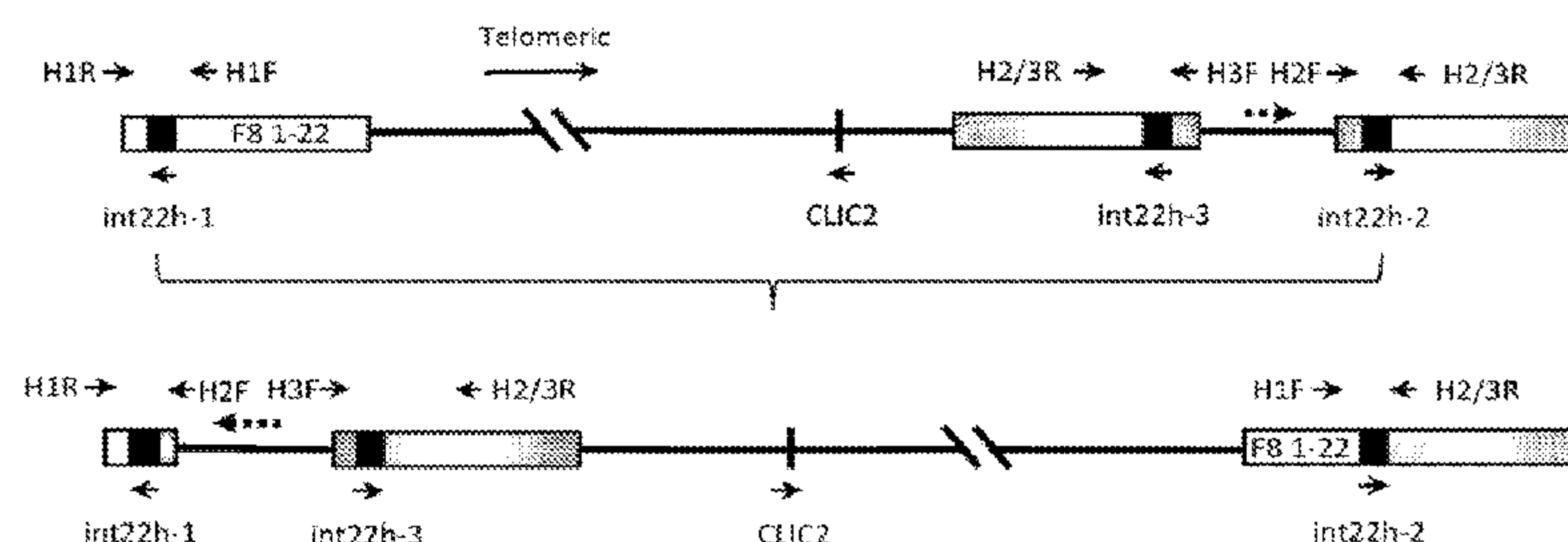


Fig. 1B



(57) Abstract: The present invention encompasses engineered nucleases which recognize and cleave a recognition sequence within the int22h-1 sequence of a Factor VIII gene. The present invention also encompasses methods of using such engineered nucleases to make genetically-modified cells, and the use of such cells in a pharmaceutical composition and in methods for treating hemophilia A. Further, the invention encompasses pharmaceutical compositions comprising engineered nuclease proteins, nucleic acids encoding engineered nucleases, or genetically -modified cells of the invention, and the use of such compositions for treating of hemophilia A.

[Continued on next page]

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ENGINEERED NUCLEASES USEFUL FOR TREATMENT OF HEMOPHILIA A**CROSS REFERENCE TO RELATED APPLICATIONS**

[0001] This application claims priority to U.S. Provisional Application No. 62/331,335, entitled “ENGINEERED NUCLEASES USEFUL FOR TREATMENT OF HEMOPHILIA A,” filed May 3, 2016, the disclosure of which is hereby incorporated by reference in its entirety.

FIELD OF THE INVENTION

[0002] The invention relates to the field of molecular biology and recombinant nucleic acid technology. In particular, the invention relates to engineered nucleases having specificity for a recognition sequence within intron 22 of a Factor VIII gene, and particularly within the int22h-1 sequence. Such engineered nucleases are useful in methods for treating hemophilia A characterized by an inversion of exons 1-22 in the Factor VIII gene.

REFERENCE TO A SEQUENCE LISTING SUBMITTED AS**A TEXT FILE VIA EFS-WEB**

[0003] The instant application contains a Sequence Listing which has been submitted in ASCII format via EFS-Web and is hereby incorporated by reference in its entirety. Said ASCII copy, created on May 2, 2017, is named 182WO1_Sequence_Listing_Final, and is 172,847 bytes in size.

BACKGROUND OF THE INVENTION

[0004] Hemophilia A is a common genetic bleeding disorder with an incidence of 1 in 5000 males worldwide. This genetic disease can result from various mutations within the coagulation Factor VIII (F8) gene located on the X chromosome, which include large deletions, insertions, inversions, and point mutations. Clinically, hemophilia A can be classified based on relative Factor VIII activity in the patient's plasma as mild (5-30% activity; 50% of patients), moderate (2-5% activity; 10% of patients), or severe (<1% activity; 50% of patients). Currently, there is no cure for hemophilia A. Standard therapy includes the administration of recombinant Factor VIII, but this approach is limited by cost, the requirement for frequent injections, and the formation of Factor VIII-inactivating antibodies in the subject which reduce the effectiveness of therapy. Therefore, a clear need

still exists for alternative treatments for hemophilia A. Gene therapy, targeting mutations in the Factor VIII gene, remains an attractive yet elusive approach to treatment.

[0005] Factor VIII is an essential component of the clotting cascade. The protein circulates in the body in an inactive form that is attached to von Willebrand factor. In response to injury, Factor VIII is activated (Factor VIIIa) and separates from von Willebrand factor, then interacts with Factor IXa as part of the clotting cascade which leads to the formation of fibrin and stable clotting. A number of studies have suggested that Factor VIII is produced by liver sinusoidal endothelial cells, as well as extra-hepatic, hematopoietic cells throughout the body.

[0006] The Factor VIII gene on the X chromosome is large and structurally complex, comprising ~180 kb and 26 exons. The wild-type Factor VIII gene encodes two proteins. The first protein is the full-length Factor VIII protein, which is encoded by the 9030 bases found in exons 1 to 26, and has a circulating form containing 2332 amino acid residues. The second protein, referred to as Factor VIIIb, is encoded by 2598 bases in 5 exons present in the Factor VIII gene. The resulting protein comprises 216 amino acids and has a presently unknown function.

[0007] Approximately 45% of severe hemophilia A cases are caused by an intra-chromosomal inversion that involves intron 22 of the Factor VIII gene. This inversion arises when an ~9.5 kb segment of intron 22, referred to as int22h-1, recombines with one of two repeat copies (referred to as int22h-2 and int22h-3, respectively) which are positioned approximately 400 kb and 500 kb telomeric to the Factor VIII gene on the X chromosome. Following recombination, exons 1-22 of the Factor VIII gene become inverted in the genome relative to exons 23-26, resulting in the expression of a truncated, inactive Factor VIII protein that lacks the amino acids encoded by exons 23-26 (Sauna et al. (2015) *Blood* 125(2): 223-228).

[0008] The upstream repeat copy involved in exon 1-22 inversion is oriented in the opposite direction as int22h-1. Early studies suggested that int22h-2 and int22h-3 were both in reverse orientation relative to int22h-1, allowing for recombination to occur with either repeat sequence. This was referred to as Type I inversion and Type II inversion. However, more recent evidence indicates that int22h-2 and int22h-3 are found in an inverse orientation to one another on the X chromosome, and are part of an imperfect palindrome (Fig. 1). Recombination of sequences within this palindrome allows int22h-2 and int22h-3 to swap places in the genome and, consequently, change their orientation relative to int22h-1. As a

result, the int22h-1 sequence can, in different circumstances, recombine with the int22h-2 repeat or the int22h-3 repeat, depending on which is in the opposite orientation to int22h-1 (Bagnall et al. (2006) *Journal of Thrombosis and Haemostasis* 4: 591-598).

[0009] Of note, intron 22 of the Factor VIII gene contains a CpG island that acts as a bi-directional promoter for two further genes, referred to as F8A1 (Factor VIII-associated 1) and F8B. The CpG island and the intron-less F8A1 gene (SEQ ID NO: 5) are both contained within the int22h-1 sequence (and consequently, within int22h-2 and int22h-3) and are transcribed in the opposite direction as the Factor VIII gene (Bowen (2002) *J. Clin. Pathol: Mol. Pathol.* 55: 127-144). Interestingly, the inventors have determined that the sequence of the F8A1 gene is the only region of the human Factor VIII gene that exhibits significant homology to the Factor VIII gene in the canine genome, and particularly in a clinically-relevant population of canines that are Factor VIII-deficient and exhibit an inversion of exons 1-22 in their Factor VIII gene (Lozier et al. (2002) *PNAS* 99(20): 12991-12996).

[0010] The present invention requires the use of site-specific, rare-cutting endonucleases that are engineered to recognize DNA sequences within the int22h-1 sequence in order to generate a double-strand break and promote recombination between int22h-1 and an inversely-oriented repeat sequence (int22h-2 or int22h-3) positioned telomeric to the Factor VIII gene. The inventors have found that nuclease-induced recombination between these regions results in an inversion or reversion of exons 1-22 of the Factor VIII gene.

[0011] Methods for producing engineered, site-specific endonucleases are known in the art. For example, zinc-finger nucleases (ZFNs) can be engineered to recognize and cut pre-determined sites in a genome. ZFNs are chimeric proteins comprising a zinc finger DNA-binding domain fused to the nuclease domain of the FokI restriction enzyme. The zinc finger domain can be redesigned through rational or experimental means to produce a protein which binds to a pre-determined DNA sequence ~18 basepairs in length. By fusing this engineered protein domain to the FokI nuclease, it is possible to target DNA breaks with genome-level specificity. ZFNs have been used extensively to target gene addition, removal, and substitution in a wide range of eukaryotic organisms (reviewed in S. Durai *et al.*, *Nucleic Acids Res* 33, 5978 (2005)).

[0012] Likewise, TAL-effector nucleases (TALENs) can be generated to cleave specific sites in genomic DNA. Like a ZFN, a TALEN comprises an engineered, site-specific DNA-binding domain fused to the FokI nuclease domain (reviewed in Mak, *et al.* (2013) *Curr Opin*

Struct Biol. 23:93-9). In this case, however, the DNA binding domain comprises a tandem array of TAL-effector domains, each of which specifically recognizes a single DNA basepair.

[0013] Compact TALENs are an alternative endonuclease architecture that avoids the need for dimerization (Beurdeley, *et al.* (2013) *Nat Commun.* 4:1762). A Compact TALEN comprises an engineered, site-specific TAL-effector DNA-binding domain fused to the nuclease domain from the I-TevI homing endonuclease. Unlike FokI, I-TevI does not need to dimerize to produce a double-strand DNA break so a Compact TALEN is functional as a monomer.

[0014] Engineered endonucleases based on the CRISPR/Cas9 system are also known in the art (Ran, *et al.* (2013) *Nat Protoc.* 8:2281-2308; Mali *et al.* (2013) *Nat Methods.* 10:957-63). A CRISPR endonuclease comprises two components: (1) a caspase effector nuclease, typically microbial Cas9; and (2) a short “guide RNA” comprising a ~20 nucleotide targeting sequence that directs the nuclease to a location of interest in the genome. By expressing multiple guide RNAs in the same cell, each having a different targeting sequence, it is possible to target DNA breaks simultaneously to multiple sites in in the genome.

[0015] In the preferred embodiment of the invention, the DNA break-inducing agent is an engineered homing endonuclease (also called a “meganuclease”). Homing endonucleases are a group of naturally-occurring nucleases which recognize 15-40 base-pair cleavage sites commonly found in the genomes of plants and fungi. They are frequently associated with parasitic DNA elements, such as group 1 self-splicing introns and inteins. They naturally promote homologous recombination or gene insertion at specific locations in the host genome by producing a double-stranded break in the chromosome, which recruits the cellular DNA-repair machinery (Stoddard (2006), *Q. Rev. Biophys.* 38: 49-95). Homing endonucleases are commonly grouped into four families: the LAGLIDADG family, the GIY-YIG family, the His-Cys box family and the HNH family. These families are characterized by structural motifs, which affect catalytic activity and recognition sequence. For instance, members of the LAGLIDADG family are characterized by having either one or two copies of the conserved LAGLIDADG motif (see Chevalier *et al.* (2001), *Nucleic Acids Res.* 29(18): 3757-3774). The LAGLIDADG homing endonucleases with a single copy of the LAGLIDADG motif form homodimers, whereas members with two copies of the LAGLIDADG motif are found as monomers.

[0016] I-CreI (SEQ ID NO: 1) is a member of the LAGLIDADG family of homing endonucleases which recognizes and cuts a 22 basepair recognition sequence in the

chloroplast chromosome of the algae *Chlamydomonas reinhardtii*. Genetic selection techniques have been used to modify the wild-type I-CreI cleavage site preference (Sussman *et al.* (2004), *J. Mol. Biol.* 342: 31-41; Chames *et al.* (2005), *Nucleic Acids Res.* 33: e178; Seligman *et al.* (2002), *Nucleic Acids Res.* 30: 3870-9, Arnould *et al.* (2006), *J. Mol. Biol.* 355: 443-58). Methods for rationally-designing mono-LAGLIDADG homing endonucleases were described which are capable of comprehensively redesigning I-CreI and other homing endonucleases to target widely-divergent DNA sites, including sites in mammalian, yeast, plant, bacterial, and viral genomes (WO 2007/047859).

[0017] As first described in WO 2009/059195, I-CreI and its engineered derivatives are normally dimeric but can be fused into a single polypeptide using a short peptide linker that joins the C-terminus of a first subunit to the N-terminus of a second subunit (Li, *et al.* (2009) *Nucleic Acids Res.* 37:1650-62; Grizot, *et al.* (2009) *Nucleic Acids Res.* 37:5405-19.) Thus, a functional “single-chain” meganuclease can be expressed from a single transcript. This, coupled with the extremely low frequency of off-target cutting observed with engineered meganucleases makes them the preferred endonuclease for the present invention.

[0018] The use of engineered nucleases for gene therapy in severe hemophilia A has been limited. Park *et al.* described the use of a TALEN to induce an inversion of exon 1 in the Factor VIII gene in HEK 293T cells and induced pluripotent stem cells (iPSCs) (Park *et al.* (2014), *PNAS* 111(25): 9253-9258). Inversions of exon 1 are also associated with the occurrence of hemophilia A occur due to homologous recombination between an int1h-1 sequence in intron 1 of the Factor VIII gene and a single homologous region (int1h-2) positioned telomeric to the Factor VIII gene. The TALEN selected for this study cut within the intron 1 homology region in order to induce an inversion of this shorter sequence with an efficiency of 1.9% and 1.4% in the HEK 293T cells and iPSCs, respectively. The authors further demonstrated reversion of exon 1 in the iPSCs at a similar efficiency of 1.3%.

[0019] In a subsequent study, Park *et al.* reported the use of a CRISPR/Cas system to induce a reversion of exons 1-22 of the Factor VIII gene in iPSCs obtained from patients suffering from severe hemophilia A (Park *et al.* (2015) *Cell Stem Cell* 17: 213-220). The authors noted that inversions of exons 1-22 are eight times more prevalent than inversions of exon 1, but emphasized that the exon 1-22 inversion is technically more challenging to revert due in part to the substantially larger size of the inversion (600 kbp compared to 140 kbp) and the presence of three homologs of the int22h-1 sequence on the X chromosome, compared to only two homologs of the int1h-1 sequence. Indeed, Park *et al.* specifically targets

recognition sequences outside of the int22h-1, int22h-2, and int22h-3 homology regions in order to rule out the possibility that unwanted deletions or inversions involving any two of the three int22 homologs, rather than the desired reversion of the inverted 600-kbp segment, would be induced by cutting within an int22h homology region. Using this approach, the authors observed a reversion frequency of approximately 3.7% in iPS cells.

[0020] The present invention improves on the art in several aspects. Despite suggestions in the art to avoid targeting recognition sequences within the int22h homology regions, the inventors surprisingly found that targeting recognition sequences within int22h-1 can, in fact, produce an inversion or reversion of exons 1-22 in the Factor VIII with high efficiency. Further, several recognition sequences targeted within the int22h-1 sequence are found within the F8A1 sequence, which the inventors found to be the only region of the Factor VIII gene which shares a high degree of homology with the canine Factor VIII gene. Thus, the methods of the invention are useful not only in human subjects suffering from hemophilia A, but also in the clinically-relevant canine hemophilia A population which also expresses an inversion of exons 1-22. Accordingly, the present invention fulfills a need in the art for further gene therapy approaches to severe hemophilia A.

SUMMARY OF THE INVENTION

[0021] The present invention provides engineered nucleases useful for the treatment of hemophilia A, which is characterized by an inversion of exons 1-22 of the Factor VIII gene. The engineered nucleases of the invention recognize and cleave a recognition sequence within an int22h-1 sequence of the Factor VIII gene, thereby promoting recombination between the int22h-1 sequence and an identical, or highly homologous, inverted repeat sequence positioned telomeric to the Factor VIII gene on the X chromosome. Such recombination results in a reversion of exons 1-22 to generate a wild-type Factor VIII gene. The present invention also provides pharmaceutical compositions and methods for treatment of hemophilia A which utilize an engineered nuclease having specificity for a recognition sequence positioned within the int22h-1 sequence of the Factor VIII gene. The present invention further provides genetically-modified cells which have been modified to correct an inversion of exons 1-22 in the Factor VIII gene, as well as pharmaceutical compositions comprising such genetically-modified cells and methods of using the same for the treatment of hemophilia A.

[0022] Thus, in one aspect, the invention provides an engineered meganuclease that recognizes and cleaves a recognition sequence within an int22h-1 sequence of a Factor VIII gene. The engineered meganuclease comprises a first subunit and a second subunit, wherein the first subunit binds to a first recognition half-site of the recognition sequence and comprises a first hypervariable (HVR1) region, and wherein the second subunit binds to a second recognition half-site of the recognition sequence and comprises a second hypervariable (HVR2) region.

[0023] In one embodiment, the int22h-1 sequence can have at least 80%, at least 85%, at least 90%, at least 95%, or more, sequence identity to SEQ ID NO: 3 or SEQ ID NO: 4. In one such embodiment, the int22h-1 sequence can comprise SEQ ID NO: 3 or SEQ ID NO: 4.

[0024] In another embodiment, the recognition sequence can be within an F8A1 coding sequence of the Factor VIII gene. In such an embodiment, the F8A1 coding sequence can have at least 80%, at least 85%, at least 90%, at least 95%, or more, sequence identity to SEQ ID NO: 5 or SEQ ID NO: 6. In another such embodiment, the F8A1 coding sequence can comprise SEQ ID NO: 5 or SEQ ID NO: 6.

[0025] In another embodiment, the recognition sequence can comprise SEQ ID NO: 7.

[0026] In some such embodiments, the HVR1 region can comprise an amino acid sequence having at least 80% sequence identity to an amino acid sequence corresponding to residues 215-270 of SEQ ID NO: 19 or residues 24-79 of any one of SEQ ID NOs: 20-21.

[0027] In certain embodiments, the HVR1 region can comprise residues corresponding to residues 215, 217, 219, 221, 223, 224, 229, 231, 233, 235, 237, 259, 261, 266, and 268 of SEQ ID NO: 19 or residues 24, 26, 28, 30, 32, 33, 38, 40, 42, 44, 46, 68, 70, 75, and 77 of any one of SEQ ID NOs: 20-21.

[0028] In particular embodiments, the HVR1 region can comprise residues 215-270 of SEQ ID NO: 19 or residues 24-79 of any one of SEQ ID NOs: 20-21.

[0029] In some such embodiments, the HVR2 region can comprise an amino acid sequence having at least 80% sequence identity to an amino acid sequence corresponding to residues 24-79 of SEQ ID NO: 19 or residues 215-270 of any one of SEQ ID NOs: 20-21.

[0030] In certain embodiments, the HVR2 region can comprise residues corresponding to residues 24, 26, 28, 30, 32, 33, 38, 40, 42, 44, 68, 70, 75, and 77 of SEQ ID NO: 19 or residues 215, 217, 219, 221, 223, 224, 229, 231, 233, 235, 259, 261, 266, and 268 of any one of SEQ ID NOs: 20-21.

[0031] In particular embodiments, the HVR2 region can comprise residues 24-79 of SEQ ID NO: 19 or residues 215-270 of any one of SEQ ID NOs: 20-21.

[0032] In one such embodiment, the first subunit can comprise an amino acid sequence having at least 80%, at least 85%, at least 90%, at least 95%, or more, sequence identity to residues 198-344 of SEQ ID NO: 19 or residues 7-153 of SEQ ID NO: 20 or 21, and the second subunit can comprise an amino acid sequence having at least 80%, at least 85%, at least 90%, at least 95, or more, sequence identity to residues 7-153 of SEQ ID NO: 19 or residues 198-344 of SEQ ID NO: 20 or 21.

[0033] In another such embodiment, the first subunit can comprise residues 198-344 of SEQ ID NO: 19 or residues 7-153 of SEQ ID NO: 20 or 21. In another such embodiment, the second subunit can comprise residues 7-153 of SEQ ID NO: 19 or residues 198-344 of SEQ ID NO: 20 or 21.

[0034] In another such embodiment, the engineered meganuclease can be a single-chain meganuclease comprising a linker, wherein the linker covalently joins the first subunit and the second subunit.

[0035] In another such embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 19-21.

[0036] In another embodiment, the recognition sequence can comprise SEQ ID NO: 9.

[0037] In some such embodiments, the HVR1 region can comprise an amino acid sequence having at least 80% sequence identity to an amino acid sequence corresponding to residues 215-270 of any one of SEQ ID NOs: 28-31.

[0038] In certain embodiments, the HVR1 region can comprise residues corresponding to residues 215, 217, 219, 221, 223, 224, 231, 233, 235, 237, 261, 266, and 268 of any one of SEQ ID NOs: 28-31.

[0039] In particular embodiments, the HVR1 region can comprise residues 215-270 of any one of SEQ ID NOs: 28-31.

[0040] In some such embodiments, the HVR2 region can comprise an amino acid sequence having at least 80% sequence identity to an amino acid sequence corresponding to residues 24-79 of any one of SEQ ID NOs: 28-31.

[0041] In certain embodiments, the HVR2 region can comprise residues corresponding to residues 24, 26, 28, 30, 32, 33, 38, 40, 42, 44, 46, 68, 70, 75, and 77 of any one of SEQ ID NOs: 28-31.

[0042] In further embodiments, the HVR2 region further can comprise a residue corresponding to residue 73 of SEQ ID NO: 30.

[0043] In particular embodiments, the HVR2 region can comprise residues 24-79 of any one of SEQ ID NOs: 28-31.

[0044] In one such embodiment, the first subunit can comprise an amino acid sequence having at least 80%, at least 85%, at least 90%, at least 95%, or more, sequence identity to residues 198-344 of any one of SEQ ID NOs: 28-31, and the second subunit can comprise an amino acid sequence having at least 80%, at least 85%, at least 90%, at least 95%, or more, sequence identity to residues 7-153 of any one of SEQ ID NOs: 28-31.

[0045] In another such embodiment, the first subunit can comprise residues 198-344 of any one of SEQ ID NOs: 28-31. In another such embodiment, the second subunit can comprise residues 7-153 of any one of SEQ ID NOs: 28-31.

[0046] In another such embodiment, the engineered meganuclease is a single-chain meganuclease comprising a linker, wherein the linker covalently joins the first subunit and the second subunit.

[0047] In another such embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 28-31.

[0048] In another embodiment, the recognition sequence can comprise SEQ ID NO: 11.

[0049] In some such embodiments, the HVR1 region can comprise an amino acid sequence having at least 80% sequence identity to an amino acid sequence corresponding to residues 24-79 of SEQ ID NO: 40 or residues 215-270 of any one of SEQ ID NOs: 41-43.

[0050] In certain embodiments, the HVR1 region can comprise residues corresponding to residues 24, 26, 28, 30, 32, 33, 38, 40, 42, 44, 46, 68, 70, 75, and 77 of SEQ ID NO: 40 or residues 215, 217, 219, 221, 223, 224, 229, 231, 233, 235, 237, 259, 261, 266, and 268 of any one of SEQ ID NOs: 41-43.

[0051] In particular embodiments, the HVR1 region can comprise residues 24-79 of SEQ ID NO: 40 or residues 215-270 of any one of SEQ ID NOs: 41-43.

[0052] In some such embodiments, the HVR2 region can comprise an amino acid sequence having at least 80% sequence identity to an amino acid sequence corresponding to residues 215-270 of SEQ ID NO: 40 or residues 24-79 of any one of SEQ ID NOs: 41-43.

[0053] In certain embodiments, the HVR2 region can comprise residues corresponding to residues 215, 217, 219, 221, 223, 224, 229, 231, 233, 235, 237, 259, 261, 266, and 268 of

SEQ ID NO: 40 or residues 24, 26, 28, 30, 32, 33, 38, 40, 42, 44, 46, 68, 70, 75, and 77 of any one of SEQ ID NOs: 41-43.

[0054] In particular embodiments, the HVR2 region can comprise residues 215-270 of SEQ ID NO: 40 or residues 24-79 of any one of SEQ ID NOs: 41-43.

[0055] In one such embodiment, the first subunit can comprise an amino acid sequence having at least 80%, at least 85%, at least 90%, at least 95%, or more, sequence identity to residues 7-153 of SEQ ID NO: 40 or residues 198-344 of any one of SEQ ID NOs: 41-43, and the second subunit can comprise an amino acid sequence having at least 80%, at least 85%, at least 90%, at least 95%, or more, sequence identity to residues 198-344 of SEQ ID NO: 40 or residues 7-153 of any one of SEQ ID NOs: 41-43.

[0056] In another such embodiment, the first subunit can comprise residues 7-153 of SEQ ID NO: 40 or residues 198-344 of any one of SEQ ID NOs: 41-43. In another such embodiment, the second subunit can comprise residues 198-344 of SEQ ID NO: 40 or residues 7-153 of any one of SEQ ID NOs: 41-43.

[0057] In another such embodiment, the engineered meganuclease is a single-chain meganuclease comprising a linker, wherein the linker covalently joins the first subunit and the second subunit.

[0058] In another such embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 40-43.

[0059] In another embodiment, the recognition sequence can comprise SEQ ID NO: 13.

[0060] In some such embodiments, the HVR1 region can comprise an amino acid sequence having at least 80% sequence identity to an amino acid sequence corresponding to residues 24-79 of any one of SEQ ID NOs: 52-55.

[0061] In certain embodiments, the HVR1 region can comprise residues corresponding to residues 24, 26, 28, 30, 32, 33, 38, 40, 42, 44, 68, 70, 75, and 77 of any one of SEQ ID NOs: 52-55.

[0062] In particular embodiments, the HVR1 region can comprise residues 24-79 of any one of SEQ ID NOs: 52-55.

[0063] In some such embodiments, the HVR2 region can comprise an amino acid sequence having at least 80% sequence identity to an amino acid sequence corresponding to residues 215-270 of any one of SEQ ID NOs: 52-55.

[0064] In certain embodiments, the HVR2 region can comprise residues corresponding to residues 215, 217, 219, 221, 223, 224, 229, 231, 233, 235, 237, 259, 261, 266, and 268 of any one of SEQ ID NOs: 52-55.

[0065] In particular embodiments, the HVR2 region can comprise residues 215-270 of any one of SEQ ID NOs: 52-55.

[0066] In one such embodiment, the first subunit can comprise an amino acid sequence having at least 80%, at least 85%, at least 90%, at least 95%, or more, sequence identity to residues 7-153 of any one of SEQ ID NOs: 52-55, and the second subunit can comprise an amino acid sequence having at least 80%, at least 85%, at least 90%, at least 95%, or more, sequence identity to residues 198-344 of any one of SEQ ID NOs: 52-55.

[0067] In another such embodiment, the first subunit can comprise residues 7-153 of any one of SEQ ID NOs: 52-55. In another such embodiment, the second subunit can comprise residues 198-344 of any one of SEQ ID NOs: 52-55.

[0068] In another such embodiment, the engineered meganuclease is a single-chain meganuclease comprising a linker, wherein the linker covalently joins the first subunit and the second subunit.

[0069] In another such embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 52-55.

[0070] In another embodiment, the recognition sequence can comprise SEQ ID NO: 15.

[0071] In some such embodiments, the HVR1 region can comprise an amino acid sequence having at least 80% sequence identity to an amino acid sequence corresponding to residues 24-79 of SEQ ID NO: 64 or residues 215-270 of any one of SEQ ID NOs: 65-67.

[0072] In certain embodiments, the HVR1 region can comprise residues corresponding to residues 24, 26, 28, 30, 32, 33, 40, 42, 44, 46, 68, 70, 75, and 77 of SEQ ID NO: 64 or residues 215, 217, 219, 221, 223, 224, 231, 233, 235, 237, 259, 261, 266, and 268 of any one of SEQ ID NOs: 65-67.

[0073] In particular embodiments, the HVR1 region can comprise residues 24-79 of SEQ ID NO: 64 or residues 215-270 of any one of SEQ ID NOs: 65-67.

[0074] In some such embodiments, the HVR2 region can comprise an amino acid sequence having at least 80% sequence identity to an amino acid sequence corresponding to residues 215-270 of SEQ ID NO: 64 or residues 24-79 of any one of SEQ ID NOs: 65-67.

[0075] In certain embodiments, the HVR2 region can comprise residues corresponding to residues 215, 217, 219, 221, 223, 224, 229, 231, 233, 235, 237, 259, 261, 266, and 268 of

SEQ ID NO: 64 or residues 24, 26, 28, 30, 32, 33, 38, 40, 42, 44, 46, 68, 70, 75, and 77 of any one of SEQ ID NOs: 65-67.

[0076] In particular embodiments, the HVR2 region can comprise residues 215-270 of SEQ ID NO: 64 or residues 24-79 of any one of SEQ ID NOs: 65-67.

[0077] In one such embodiment, the first subunit can comprise an amino acid sequence having at least 80%, at least 85%, at least 90%, at least 95%, or more, sequence identity to residues 7-153 of SEQ ID NO: 64 or residues 198-344 of any one of SEQ ID NOs: 65-67, and the second subunit can comprise an amino acid sequence having at least 80%, at least 85%, at least 90%, at least 95%, or more, sequence identity to residues 198-344 of SEQ ID NO: 64 or residues 7-153 of any one of SEQ ID NOs: 65-67.

[0078] In another such embodiment, the first subunit can comprise residues 7-153 of SEQ ID NO: 64 or residues 198-344 of any one of SEQ ID NOs: 65-67. In another such embodiment, the second subunit can comprise residues 198-344 of SEQ ID NO: 64 or residues 7-153 of any one of SEQ ID NOs: 65-67.

[0079] In another such embodiment, the engineered meganuclease is a single-chain meganuclease comprising a linker, wherein the linker covalently joins the first subunit and the second subunit.

[0080] In another such embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 64-67.

[0081] In another embodiment, the recognition sequence can comprise SEQ ID NO: 17.

[0082] In some such embodiments, the HVR1 region can comprise an amino acid sequence having at least 80% sequence identity to an amino acid sequence corresponding to residues 215-270 of any one of SEQ ID NOs: 76-79.

[0083] In certain embodiments, the HVR1 region can comprise residues corresponding to residues 215, 217, 219, 221, 223, 224, 229, 231, 233, 235, 259, 261, 266, and 268 of any one of SEQ ID NOs: 76-79.

[0084] In particular embodiments, the HVR1 region can comprise residues 215-270 of any one of SEQ ID NOs: 76-79.

[0085] In some such embodiments, the HVR2 region can comprise an amino acid sequence having at least 80% sequence identity to an amino acid sequence corresponding to residues 24-79 of any one of SEQ ID NOs: 76-79.

[0086] In certain embodiments, the HVR2 region can comprise residues corresponding to residues 24, 26, 28, 30, 32, 33, 38, 40, 42, 44, 46, 68, 70, 75, and 77 of any one of SEQ ID NOs: 76-79.

[0087] In particular embodiments, the HVR2 region can comprise residues 24-79 of any one of SEQ ID NOs: 76-79.

[0088] In one such embodiment, the first subunit can comprise an amino acid sequence having at least 80%, at least 85%, at least 90%, at least 95%, or more, sequence identity to residues 198-344 of any one of SEQ ID NOs: 76-79, and the second subunit can comprise an amino acid sequence having at least 80%, at least 85%, at least 90%, at least 95%, or more, sequence identity to residues 7-153 of any one of SEQ ID NOs: 76-79.

[0089] In another such embodiment, the first subunit can comprise residues 198-344 of any one of SEQ ID NOs: 76-79. In another such embodiment, the second subunit can comprise residues 7-153 of any one of SEQ ID NOs: 76-79.

[0090] In another such embodiment, the engineered meganuclease is a single-chain meganuclease comprising a linker, wherein the linker covalently joins the first subunit and the second subunit.

[0091] In another such embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 76-79.

[0092] In another aspect, the invention provides an isolated polynucleotide comprising a nucleic acid sequence encoding any engineered meganuclease of the invention. In a particular embodiment, the isolated polynucleotide can be an mRNA.

[0093] In another aspect, the invention provides a recombinant DNA construct comprising a nucleic acid sequence which encodes any engineered meganuclease of the invention.

[0094] In one embodiment, the recombinant DNA construct can be self-cleaving.

[0095] In another embodiment, the recombinant DNA construct encodes a viral vector. In such an embodiment, the viral vector can be a retrovirus, a lentivirus, an adenovirus, or an adeno-associated virus (AAV) vector. In a particular embodiment, the viral vector can be a recombinant AAV vector.

[0096] In another aspect, the invention provides a viral vector comprising a nucleic acid sequence which encodes any engineered meganuclease of the invention.

[0097] In one embodiment, the viral vector can be a retrovirus, a lentivirus, an adenovirus, or an adeno-associated virus (AAV) vector. In a particular embodiment, the viral vector can be a recombinant AAV vector.

[0098] In another aspect, the invention provides a pharmaceutical composition for treatment of a subject having hemophilia A. In such an aspect, hemophilia A is characterized by an inversion of exons 1-22 in a Factor VIII gene. The pharmaceutical composition comprises a pharmaceutically acceptable carrier and: (a) a nucleic acid encoding an engineered nuclease, wherein the engineered nuclease is expressed in a target cell in vivo; or (b) an engineered nuclease protein; wherein the engineered nuclease has specificity for a first recognition sequence positioned within an int22h-1 sequence of the Factor VIII gene in the target cell.

[0099] In one embodiment, the int22h-1 sequence can have at least 80%, at least 85%, at least 90%, at least 95%, or more, sequence identity to SEQ ID NO: 3 or SEQ ID NO: 4. In one such embodiment, the int22h-1 sequence can comprise SEQ ID NO: 3 or SEQ ID NO: 4.

[0100] In another embodiment, the first recognition sequence can be within an F8A1 coding sequence. In such an embodiment, the F8A1 coding sequence can have at least 80%, at least 85%, at least 90%, at least 95%, or more sequence identity to SEQ ID NO: 5 or SEQ ID NO: 6. In another such embodiment, the F8A1 coding sequence can comprise SEQ ID NO: 5 or SEQ ID NO: 6.

[0101] In another embodiment, the engineered nuclease can have specificity for a second recognition sequence that is identical to, or has a high degree of homology with, the first recognition sequence, wherein the second recognition sequence is positioned in a repeat sequence telomeric to the Factor VIII gene in the X chromosome. In such an embodiment, the repeat sequence is identical to, or has a high degree of homology with, the int22h-1 sequence except that the repeat sequence is in reverse orientation relative to the int22h-1 sequence.

[0102] In another embodiment, the nucleic acid encoding the engineered nuclease can be an mRNA.

[0103] In another embodiment, the pharmaceutical composition comprises a recombinant DNA construct comprising the nucleic acid. In one such embodiment, the recombinant DNA construct can be self-cleaving.

[0104] In another embodiment, the pharmaceutical composition comprises a viral vector comprising the nucleic acid. In one such embodiment, the viral vector can be a retrovirus, a

lentivirus, an adenovirus, or an AAV. In a particular embodiment, the viral vector can be a recombinant AAV vector.

[0105] In another embodiment, the engineered nuclease can be an engineered meganuclease, a TALEN, a zinc finger nuclease, a compact TALEN, a CRISPR, or a megaTAL. In a particular embodiment, the engineered nuclease can be an engineered meganuclease.

[0106] In another embodiment, wherein the engineered nuclease is an engineered meganuclease, the first recognition sequence can comprise SEQ ID NO: 7. In one such embodiment, the pharmaceutical composition can comprise an engineered meganuclease of the invention (or a nucleic acid encoding the same) which recognizes and cleaves SEQ ID NO: 7. In a particular embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 19-21.

[0107] In another embodiment, wherein the engineered nuclease is an engineered meganuclease, the first recognition sequence can comprise SEQ ID NO: 9. In one such embodiment, the pharmaceutical composition can comprise an engineered meganuclease of the invention (or a nucleic acid encoding the same) which recognizes and cleaves SEQ ID NO: 9. In a particular embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 28-31.

[0108] In another embodiment, wherein the engineered nuclease is an engineered meganuclease, the first recognition sequence can comprise SEQ ID NO: 11. In one such embodiment, the pharmaceutical composition can comprise an engineered meganuclease of the invention (or a nucleic acid encoding the same) which recognizes and cleaves SEQ ID NO: 11. In a particular embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 40-43.

[0109] In another embodiment, wherein the engineered nuclease is an engineered meganuclease, the first recognition sequence can comprise SEQ ID NO: 13. In one such embodiment, the pharmaceutical composition can comprise an engineered meganuclease of the invention (or a nucleic acid encoding the same) which recognizes and cleaves SEQ ID NO: 13. In a particular embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 52-55.

[0110] In another embodiment, wherein the engineered nuclease is an engineered meganuclease, the first recognition sequence can comprise SEQ ID NO: 15. In one such embodiment, the pharmaceutical composition can comprise an engineered meganuclease of

the invention (or a nucleic acid encoding the same) which recognizes and cleaves SEQ ID NO: 15. In a particular embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 64-67.

[0111] In another embodiment, wherein the engineered nuclease is an engineered meganuclease, the first recognition sequence can comprise SEQ ID NO: 17. In one such embodiment, the pharmaceutical composition can comprise an engineered meganuclease of the invention (or a nucleic acid encoding the same) which recognizes and cleaves SEQ ID NO: 17. In a particular embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 76-79.

[0112] In another aspect, the invention provides a method for treating a subject having hemophilia A. In such an aspect, hemophilia A is characterized by an inversion of exons 1-22 of a Factor VIII gene. The method comprises delivering to a target cell in the subject: (a) a nucleic acid encoding an engineered nuclease, wherein the engineered nuclease is expressed in the target cell in vivo; or (b) an engineered nuclease protein; wherein the engineered nuclease is any engineered nuclease of the invention which has specificity for a first recognition sequence positioned within an int22h-1 sequence of the Factor VIII gene in the target cell.

[0113] In one embodiment of the method, the method comprises administering to the subject a pharmaceutical composition of the invention described above, which comprises (a) a nucleic acid encoding an engineered nuclease of the invention, wherein the engineered nuclease is expressed in a target cell in vivo; or (b) an engineered nuclease protein of the invention.

[0114] In another embodiment of the method, the engineered nuclease, or the nucleic acid encoding the engineered nuclease, can be delivered to a target cell which is capable of expressing wild-type Factor VIII, or a progenitor cell which differentiates into a cell which is capable of expressing wild-type Factor VIII. In one such embodiment, the target cell can be a hepatic cell. In a particular embodiment, the hepatic cell can be a hepatic sinusoidal endothelial cell. In another such embodiment, the hepatic cell can be a progenitor cell, such as a hepatic stem cell, which differentiates into a hepatic sinusoidal endothelial cell. In another such embodiment, the target cell can be a hematopoietic endothelial cell. In another such embodiment, the target cell can be a progenitor cell which differentiates into a hematopoietic endothelial cell. It is understood that target cells comprise a Factor VIII gene which has an inversion of exons 1-22.

[0115] In another embodiment of the method, the engineered nuclease recognizes and cleaves the first recognition sequence to promote recombination between the int22h-1 sequence and the repeat sequence, resulting in reversion of exons 1-22 to generate a wild-type Factor VIII gene.

[0116] In another embodiment of the method, the engineered nuclease further recognizes and cleaves the second recognition sequence in the repeat sequence.

[0117] In another embodiment of the method, the engineered nuclease can be an engineered meganuclease, a TALEN, a zinc finger nuclease, a compact TALEN, a CRISPR, or a megaTAL. In a particular embodiment, the engineered nuclease can be an engineered meganuclease.

[0118] In another embodiment of the method, wherein the engineered nuclease is an engineered meganuclease, the first recognition sequence can comprise SEQ ID NO: 7. In one such embodiment, the engineered meganuclease can be any engineered meganuclease of the invention which recognizes and cleaves SEQ ID NO: 7. In a particular embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 19-21.

[0119] In another embodiment of the method, wherein the engineered nuclease is an engineered meganuclease, the first recognition sequence can comprise SEQ ID NO: 9. In one such embodiment, the engineered meganuclease can be any engineered meganuclease of the invention which recognizes and cleaves SEQ ID NO: 9. In a particular embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 28-31.

[0120] In another embodiment of the method, wherein the engineered nuclease is an engineered meganuclease, the first recognition sequence can comprise SEQ ID NO: 11. In one such embodiment, the engineered meganuclease can be any engineered meganuclease of the invention which recognizes and cleaves SEQ ID NO: 11. In a particular embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 40-43.

[0121] In another embodiment of the method, wherein the engineered nuclease is an engineered meganuclease, the first recognition sequence can comprise SEQ ID NO: 13. In one such embodiment, the engineered meganuclease can be any engineered meganuclease of the invention which recognizes and cleaves SEQ ID NO: 13. In a particular embodiment, the

engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 52-55.

[0122] In another embodiment of the method, wherein the engineered nuclease is an engineered meganuclease, the first recognition sequence can comprise SEQ ID NO: 15. In one such embodiment, the engineered meganuclease can be any engineered meganuclease of the invention which recognizes and cleaves SEQ ID NO: 15. In a particular embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 64-67.

[0123] In another embodiment of the method, wherein the engineered nuclease is an engineered meganuclease, the first recognition sequence can comprise SEQ ID NO: 17. In one such embodiment, the engineered meganuclease can be any engineered meganuclease of the invention which recognizes and cleaves SEQ ID NO: 17. In a particular embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 76-79.

[0124] In another embodiment of the method, the subject can be a mammal. In one such embodiment, the subject can be a human. In another such embodiment, the subject can be a canine.

[0125] In another aspect, the invention provides a method for producing a genetically-modified cell comprising a wild-type Factor VIII gene. The method comprises: (a) obtaining a cell comprising a Factor VIII gene having an inversion of exons 1-22; and (b) introducing into the cell: (i) a nucleic acid sequence encoding an engineered nuclease, wherein the engineered nuclease is expressed in the cell; or (ii) an engineered nuclease protein; wherein the engineered nuclease has specificity for a first recognition sequence within an int22h-1 sequence of the Factor VIII gene; and wherein the engineered nuclease recognizes and cleaves the first recognition sequence within the int22h-1 sequence to promote recombination between the int22h-1 sequence and a repeat sequence positioned telomeric to the Factor VIII gene; and wherein the repeat sequence is identical to, or has a high degree of homology with, the int22h-1 sequence except that the repeat sequence is in reverse orientation relative to the int22h-1 sequence; and wherein recombination causes reversion of exons 1-22 and generation of the genetically-modified cell comprising a wild-type Factor VIII gene.

[0126] In one embodiment, the cell can be a eukaryotic cell. In one such embodiment, the eukaryotic cell can be a pluripotent cell. In such an embodiment, the pluripotent cell can

be an induced pluripotent stem (iPS) cell. In a particular embodiment, the iPS cell can be a human iPS cell or a canine iPS cell.

[0127] In another embodiment, the int22h-1 sequence can have at least 80%, at least 85%, at least 90%, at least 95%, or more, sequence identity to SEQ ID NO: 3 or SEQ ID NO: 4. In one such embodiment, the int22h-1 sequence can comprise SEQ ID NO: 3 or SEQ ID NO: 4.

[0128] In another embodiment, the first recognition sequence can be within an F8A1 coding sequence of the Factor VIII gene. In such an embodiment, the F8A1 coding sequence can have at least 80%, at least 85%, at least 90%, at least 95%, or more, sequence identity to SEQ ID NO: 3 or SEQ ID NO: 4. In a particular embodiment, the F8A1 coding sequence can comprise SEQ ID NO: 3 or SEQ ID NO: 4.

[0129] In another embodiment, the engineered nuclease can have specificity for a second recognition sequence that is identical to, or has a high degree of homology with, the first recognition sequence, wherein the second recognition sequence is positioned in a repeat sequence telomeric to the Factor VIII gene in the X chromosome. In such an embodiment, the repeat sequence is identical to, or has a high degree of homology with, the int22h-1 sequence except that the repeat sequence is in reverse orientation relative to the int22h-1 sequence.

[0130] In another embodiment, the nucleic acid can be an mRNA.

[0131] In another embodiment, the nucleic acid can be introduced into the cell using a recombinant DNA construct. In one such embodiment, the recombinant DNA construct can be self-cleaving.

[0132] In another embodiment, the nucleic acid can be introduced into the cell using a viral vector. In one such embodiment, the viral vector can be a retrovirus, a lentivirus, an adenovirus, or an AAV. In a particular embodiment, the viral vector can be a recombinant AAV vector.

[0133] In another embodiment, the engineered nuclease can be an engineered meganuclease, a TALEN, a zinc finger nuclease, a compact TALEN, a CRISPR, or a megaTAL. In a particular embodiment, the engineered nuclease can be an engineered meganuclease.

[0134] In another embodiment, the engineered nuclease can be any engineered meganuclease of the invention which recognizes and cleaves a recognition sequence

comprising SEQ ID NO: 7. In one such embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 19-21.

[0135] In another embodiment, the engineered nuclease can be any engineered meganuclease of the invention which recognizes and cleaves a recognition sequence comprising SEQ ID NO: 9. In one such embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 28-31.

[0136] In another embodiment, the engineered nuclease can be any engineered meganuclease of the invention which recognizes and cleaves a recognition sequence comprising SEQ ID NO: 11. In one such embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 40-43.

[0137] In another embodiment, the engineered nuclease can be any engineered meganuclease of the invention which recognizes and cleaves a recognition sequence comprising SEQ ID NO: 13. In one such embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 52-55.

[0138] In another embodiment, the engineered nuclease can be any engineered meganuclease of the invention which recognizes and cleaves a recognition sequence comprising SEQ ID NO: 15. In one such embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 64-67.

[0139] In another embodiment, the engineered nuclease can be any engineered meganuclease of the invention which recognizes and cleaves a recognition sequence comprising SEQ ID NO: 17. In one such embodiment, the engineered meganuclease can comprise the amino acid sequence of any one of SEQ ID NOs: 76-79.

[0140] In another aspect, the invention provides a genetically-modified cell, wherein the genetically-modified cell comprises a wild-type Factor VIII gene and is produced according to the methods of the invention described herein, which produce a genetically-modified cell from a cell which comprises a Factor VIII gene having an inversion of exons 1-22.

[0141] In another aspect, the invention provides a pharmaceutical composition for treatment of a subject having hemophilia A. In such an aspect, hemophilia A is characterized by an inversion of exons 1-22 in a Factor VIII gene. In different embodiments, the pharmaceutical composition comprises a pharmaceutically acceptable carrier and any genetically-modified cell of the invention, and/or any genetically-modified cell produced according to the methods of the invention, which comprises a wild-type Factor VIII gene.

[0142] In another aspect, the invention provides a method for treating a subject having hemophilia A. In such an aspect, hemophilia A is characterized by an inversion of exons 1-22 of the Factor VIII gene. The method comprises administering to the subject a pharmaceutical composition of the invention which comprises a pharmaceutically acceptable carrier and any genetically-modified cell of the invention. Such a genetically-modified cell comprises a wild-type Factor VIII gene following modification.

[0143] In one embodiment of the method, the genetically-modified cell can be delivered to a target tissue. In one such embodiment, the target tissue can be the liver. In another such embodiment, the target tissue can be the circulatory system.

[0144] In another embodiment of the method, the genetically-modified cell can be a genetically-modified iPS cell. In one such embodiment, the genetically-modified iPS cell can differentiate into a cell which expresses Factor VIII when it is delivered to the target tissue. In a particular embodiment, the genetically-modified iPS cell can differentiate into a hepatic sinusoidal endothelial cell which expresses Factor VIII. In another particular embodiment, the genetically-modified iPS cell can differentiate into a hematopoietic cell, such as a hematopoietic endothelial cell, which expresses Factor VIII.

[0145] In another embodiment of the method, the subject can be a mammal. In one such embodiment, the subject can be a human. In another such embodiment, the subject can be a canine.

[0146] In another aspect, the invention provides an engineered nuclease, and particularly an engineered meganuclease, described herein for use as a medicament. The invention further provides the use of an engineered nuclease, and particularly an engineered meganuclease, described herein in the manufacture of a medicament for treating hemophilia A, which is characterized by an inversion of exons 1-22 in the Factor VIII gene.

[0147] In another aspect, the invention provides an isolated polynucleotide for use as a medicament, wherein the isolated polynucleotide comprises a nucleic acid sequence encoding an engineered nuclease, and particularly an engineered meganuclease, of the invention. The invention further provides the use of an isolated polynucleotide in the manufacture of a medicament for treating hemophilia A, which is characterized by an inversion of exons 1-22 in the Factor VIII gene, wherein the isolated polynucleotide comprises a nucleic acid sequence encoding an engineered nuclease, and particularly an engineered meganuclease, of the invention.

[0148] In another aspect, the invention provides a recombinant AAV vector for use as a medicament, wherein the recombinant AAV vector comprises an isolated polynucleotide, and wherein the isolated polynucleotide comprises a nucleic acid sequence encoding an engineered nuclease, and particularly an engineered meganuclease, of the invention. The invention further provides the use of a recombinant AAV vector in the manufacture of a medicament for treating hemophilia A, which is characterized by an inversion of exons 1-22 of the Factor VIII gene, wherein the recombinant AAV vector comprises an isolated polynucleotide, and wherein the isolated polynucleotide comprises a nucleic acid sequence encoding an engineered nuclease, and particularly an engineered meganuclease, of the invention.

[0149] In another aspect, the invention provides a genetically-modified cell of the invention for use as a medicament, wherein the genetically-modified cell has been modified to comprise a wild-type Factor VIII gene. The invention further provides the use of a genetically-modified cell of the invention in the manufacture of a medicament for treating hemophilia A, which is characterized by an inversion of exons 1-22 of the Factor VIII gene, wherein the genetically-modified cell has been modified to comprise a wild-type Factor VIII gene.

BRIEF DESCRIPTION OF THE FIGURES

[0150] Fig. 1A and Fig. 1B. Inversion of introns 1-22 in the Factor VIII gene. The int22h-2 and int22h-3 repeat sequences are positioned telomeric to the int22h-1 sequence on the X chromosome. Further, int22h-2 and int22h-3 are found in an inverse orientation to one another as part of an imperfect palindrome. Recombination of sequences within this palindrome allows int22h-2 and int22h-3 to swap places in the genome and, consequently, change their orientation relative to int22h-1. As a result, the int22h-1 sequence can, in different circumstances, recombine with the int22h-2 repeat or the int22h-3 repeat, depending on which is in the opposite orientation to int22h-1. Fig. 1A shows a configuration in which int22h-3 is in an inverse orientation to int22h-1, allowing for intrachromosomal recombination to occur between these repeat sequences, resulting in the illustrated inversion of exons 1-22. Fig. 1B shows a configuration in which int22h-2 is in an inverse orientation to int22h-1, allowing for intrachromosomal recombination to occur between these repeat sequences, resulting in the illustrated inversion of exons 1-22.

[0151] Fig. 2. F8R recognition sequences in the Factor VIII gene. A) Each recognition sequence targeted by a recombinant meganuclease of the invention comprises two recognition half-sites. Each recognition half-site comprises 9 base pairs, separated by a 4 base pair central sequence. The F8R 1-2 recognition sequence (SEQ ID NO: 7) comprises two recognition half-sites referred to as F8R1 and F8R2. The F8R 3-4 recognition sequence (SEQ ID NO: 9) comprises two recognition half-sites referred to as F8R3 and F8R4. The F8R 9-10 recognition sequence (SEQ ID NO: 11) comprises two recognition half-sites referred to as F8R9 and F8R10. The F8R 11-12 recognition sequence (SEQ ID NO: 13) comprises two recognition half-sites referred to as F8R11 and F8R12. The F8R 13-14 recognition sequence (SEQ ID NO: 15) comprises two recognition half-sites referred to as F8R13 and F8R14. The F8R 15-16 recognition sequence (SEQ ID NO: 17) comprises two recognition half-sites referred to as F8R15 and F8R16.

[0152] Fig. 3. The recombinant meganucleases of the invention comprise two subunits, wherein the first subunit comprising the HVR1 region binds to a first recognition half-site (*e.g.*, F8R1, F8R3, F8R9, F8R11, F8R13, or F8R15) and the second subunit comprising the HVR2 region binds to a second recognition half-site (*e.g.*, F8R2, F8R4, F8R10, F8R12, F8R14, or F8R16). In embodiments where the recombinant meganuclease is a single-chain meganuclease, the first subunit comprising the HVR1 region can be positioned as either the N-terminal or C-terminal subunit. Likewise, the second subunit comprising the HVR2 region can be positioned as either the N-terminal or C-terminal subunit.

[0153] Fig. 4. Schematic of reporter assay in CHO cells for evaluating recombinant meganucleases targeting recognition sequences found in intron 22 of the Factor VIII gene. For the recombinant meganucleases described herein, a CHO cell line was produced in which a reporter cassette was integrated stably into the genome of the cell. The reporter cassette comprised, in 5' to 3' order: an SV40 Early Promoter; the 5' 2/3 of the GFP gene; the recognition sequence for an engineered meganuclease of the invention (*e.g.*, the F8R 1-2 recognition sequence); the recognition sequence for the CHO-23/24 meganuclease (WO/2012/167192); and the 3' 2/3 of the GFP gene. Cells stably transfected with this cassette did not express GFP in the absence of a DNA break-inducing agent. Meganucleases were introduced by transduction of plasmid DNA or mRNA encoding each meganuclease. When a DNA break was induced at either of the meganuclease recognition sequences, the duplicated regions of the GFP gene recombined with one another to produce a functional

GFP gene. The percentage of GFP-expressing cells could then be determined by flow cytometry as an indirect measure of the frequency of genome cleavage by the meganucleases.

[0154] Figs. 5A–5G. Efficiency of recombinant meganucleases for recognizing and cleaving recognition sequences in the int22h-1 sequence of the Factor VIII gene in a CHO cell reporter assay. Recombinant meganucleases set forth in SEQ ID NOs: 19-21, 28-31, 40-43, 52-55, 64-67, and 76-79 were engineered to target the F8R 1-2 recognition sequence (SEQ ID NO: 7), the F8R 3-4 recognition sequence (SEQ ID NO: 9), the F8R 9-10 recognition sequence (SEQ ID NO: 11), the F8R 11-12 recognition sequence (SEQ ID NO: 13), the F8R 13-14 recognition sequence (SEQ ID NO: 15), or the F8R 15-16 recognition sequence (SEQ ID NO: 17), and were screened for efficacy in the CHO cell reporter assay. The results shown provide the percentage of GFP-expressing cells observed in each assay, which indicates the efficacy of each meganuclease for cleaving a target recognition sequence or the CHO-23/24 recognition sequence. A negative control (bs) was further included in each assay. Fig. 5A. shows meganucleases targeting the F8R 1-2 recognition sequence. Fig. 5B and Fig. 5C show meganucleases targeting the F8R 3-4 recognition sequence. Fig. 5D shows meganucleases targeting the F8R 9-10 recognition sequence. Fig. 5E shows meganucleases targeting the F8R 11-12 recognition sequence. Fig. 5F shows meganucleases targeting the F8R 13-14 recognition sequence. Fig. 5G shows meganucleases targeting the F8R 15-16 recognition sequence.

[0155] Figs. 6A–6F. Efficiency of engineered meganucleases for recognizing and cleaving recognition sequences in the int22h-1 sequence of the Factor VIII gene in a CHO cell reporter assay. Engineered meganucleases encompassed by the invention were engineered to target the F8R 1-2 (SEQ ID NO: 7), F8R 3-4 (SEQ ID NO: 9), F8R 9-10 (SEQ ID NO: 11), F8R 11-12 (SEQ ID NO: 13), F8R 13-14 (SEQ ID NO: 15), or F8R 15-16 (SEQ ID NO: 17) recognition sequences, and were screened for efficacy in the CHO cell reporter assay at multiple time points over 12 days after nucleofection. The results shown provide the percentage of GFP-expressing cells observed in each assay over the 12 day period of analysis, which indicates the efficacy of each meganuclease for cleaving a target recognition sequence or the CHO-23/24 recognition sequence as a function of time. Fig. 6A shows F8R 1-2 meganucleases targeting the F8R 1-2 recognition sequence. Fig. 6B shows F8R 3-4 meganucleases targeting the F8R 3-4 recognition sequence. Fig. 6C shows F8R 9-10 meganucleases targeting the F8R 9-10 recognition sequence. Fig. 6D shows F8R 11-12 meganucleases targeting the F8R 11-12 recognition sequence. Fig. 6E shows F8R 13-14

meganucleases targeting the F8R 13-14 recognition sequence. Fig. 6F shows F8R 15-16 meganucleases targeting the F8R 15-16 recognition sequence.

[0156] Fig. 7. Cleavage of F8R recognition sequences in mammalian cells.

Meganucleases F8R 1-2 and F8R 3-4 were tested for the ability to cut and cause insertions and/or deletions (indels) at their recognition sites by T7 endonuclease assay in HEK 293 cells.

[0157] Fig. 8A and Fig. 8B. Inversion of exons 1-22 in the Factor VIII gene of mammalian cells. This experiment determined if cleavage of genomic DNA by F8R 1-2 and F8R 3-4 meganucleases could stimulate an inversion of exons 1-22 in the Factor VIII gene of HEK 293 cells. Genomic DNA was analyzed by PCR using a primer set which could detect normal positioning of exons 1-22 (H1R/H1F) or an inversion of exons 1-22 (H1R/H2/3R).

[0158] Fig. 9. Inversion of exons 1-22 in the Factor VIII gene of mammalian cells. This experiment determined if cleavage of genomic DNA by F8R 9-10, F8R 11-12, F8R 13-14, and F8R 15-16 meganucleases could stimulate an inversion of exons 1-22 in the Factor VIII gene of HEK 293 cells. Genomic DNA was analyzed by PCR using a primer set which could detect normal positioning of exons 1-22 (H1R/H1F) or an inversion of exons 1-22 (H1R/H2/3R). PCR analysis from day 2 and day 8 are provided for each primer set.

[0159] Fig. 10. Inversion of Factor VIII gene by F8R nucleases in 293 cells and determination of efficiency by inverse digital PCR. HEK293 cells were transfected with mRNA encoding F8R11-12x.69 or F8R13-14x.13 nucleases, respectively. At 2 days post-transfection, genomic DNA was isolated from cells and inverse digital PCR was performed to determine Factor VIII genome editing.

[0160] Fig. 11. Inversion of Factor VIII gene by F8R nucleases in primary human T cells and determination of editing by long-distance PCR. Normal human T-cells were transfected with mRNA encoding the F8R3-4x.43 nuclease. At 3 days post-transfection, genomic DNA was isolated from cells and long-distance PCR was performed to determine Factor VIII genome editing.

[0161] Figs. 12A–12B. Reversion of Factor VIII gene by F8R nucleases in primary human patient T cells and determination of editing by long-distance PCR. Hemophilia A patient T-cells were transfected with mRNA encoding F8R3-4x.43, F8R11-12x.69, or F8R15-16x.14 nucleases, respectively. At 3 days post-transfection, genomic DNA was isolated from cells and long-distance PCR was performed to determine Factor VIII genome editing. Fig. 12A shows PCR bands corresponding to a wild-type Factor VIII gene

configuration, as detected using primers H1U and H1D. Fig. 12B shows PCR bands corresponding to the hemophilia A-associated Factor VIII gene inversion, as detected using primers H3D and H1D.

BRIEF DESCRIPTION OF THE SEQUENCES

- [0162] SEQ ID NO: 1 sets forth the amino acid sequence of the wild-type I-CreI meganuclease from *Chlamydomonas reinhardtii*.
- [0163] SEQ ID NO: 2 sets forth the amino acid sequence of the LAGLIDADG motif.
- [0164] SEQ ID NO: 3 sets forth the nucleic acid sequence of a human int22h-1 sequence.
- [0165] SEQ ID NO: 4 sets forth the nucleic acid sequence of a canine int22h-1 sequence.
- [0166] SEQ ID NO: 5 sets forth the nucleic acid sequence of a human F8A1 sequence.
- [0167] SEQ ID NO: 6 sets forth the nucleic acid sequence of a canine F8A1 sequence.
- [0168] SEQ ID NO: 7 sets forth the nucleic acid sequence of the F8R 1-2 recognition sequence (sense).
- [0169] SEQ ID NO: 8 sets forth the nucleic acid sequence of the F8R 1-2 recognition sequence (antisense).
- [0170] SEQ ID NO: 9 sets forth the nucleic acid sequence of the F8R 3-4 recognition sequence (sense).
- [0171] SEQ ID NO: 10 sets forth the nucleic acid sequence of the F8R 3-4 recognition sequence (antisense).
- [0172] SEQ ID NO: 11 sets forth the nucleic acid sequence of the F8R 9-10 recognition sequence (sense).
- [0173] SEQ ID NO: 12 sets forth the nucleic acid sequence of the F8R 9-10 recognition sequence (antisense).
- [0174] SEQ ID NO: 13 sets forth the nucleic acid sequence of the F8R 11-12 recognition sequence (sense).
- [0175] SEQ ID NO: 14 sets forth the nucleic acid sequence of the F8R 11-12 recognition sequence (antisense).
- [0176] SEQ ID NO: 15 sets forth the nucleic acid sequence of the F8R 13-14 recognition sequence (sense).
- [0177] SEQ ID NO: 16 sets forth the nucleic acid sequence of the F8R 13-14 recognition sequence (antisense).

- [0178] SEQ ID NO: 17 sets forth the nucleic acid sequence of the F8R 15-16 recognition sequence (sense).
- [0179] SEQ ID NO: 18 sets forth the nucleic acid sequence of the F8R 15-16 recognition sequence (antisense).
- [0180] SEQ ID NO: 19 sets forth the amino acid sequence of the F8R 1-2x.27 meganuclease.
- [0181] SEQ ID NO: 20 sets forth the amino acid sequence of the F8R 1-2x.15 meganuclease.
- [0182] SEQ ID NO: 21 sets forth the amino acid sequence of the F8R 1-2x.9 meganuclease.
- [0183] SEQ ID NO: 22 sets forth the amino acid sequence of the F8R 1-2x.27 meganuclease F8R1-binding monomer.
- [0184] SEQ ID NO: 23 sets forth the amino acid sequence of the F8R 1-2x.15 meganuclease F8R1-binding monomer.
- [0185] SEQ ID NO: 24 sets forth the amino acid sequence of the F8R 1-2x.9 meganuclease F8R1-binding monomer.
- [0186] SEQ ID NO: 25 sets forth the amino acid sequence of the F8R 1-2x.27 meganuclease F8R2-binding monomer.
- [0187] SEQ ID NO: 26 sets forth the amino acid sequence of the F8R 1-2x.15 meganuclease F8R2-binding monomer.
- [0188] SEQ ID NO: 27 sets forth the amino acid sequence of the F8R 1-2x.9 meganuclease F8R2-binding monomer.
- [0189] SEQ ID NO: 28 sets forth the amino acid sequence of the F8R 3-4x.43 meganuclease.
- [0190] SEQ ID NO: 29 sets forth the amino acid sequence of the F8R 3-4x.70 meganuclease.
- [0191] SEQ ID NO: 30 sets forth the amino acid sequence of the F8R 3-4x.4 meganuclease.
- [0192] SEQ ID NO: 31 sets forth the amino acid sequence of the F8R 3-4L.5 meganuclease.
- [0193] SEQ ID NO: 32 sets forth the amino acid sequence of the F8R 3-4x.43 meganuclease F8R3-binding monomer.

- [0194] SEQ ID NO: 33 sets forth the amino acid sequence of the F8R 3-4x.70 meganuclease F8R3-binding monomer.
- [0195] SEQ ID NO: 34 sets forth the amino acid sequence of the F8R 3-4x.4 meganuclease F8R3-binding monomer.
- [0196] SEQ ID NO: 35 sets forth the amino acid sequence of the F8R 3-4L.5 meganuclease F8R3-binding monomer.
- [0197] SEQ ID NO: 36 sets forth the amino acid sequence of the F8R 3-4x.43 meganuclease F8R4-binding monomer.
- [0198] SEQ ID NO: 37 sets forth the amino acid sequence of the F8R 3-4x.70 meganuclease F8R4-binding monomer.
- [0199] SEQ ID NO: 38 sets forth the amino acid sequence of the F8R 3-4x.4 meganuclease F8R4-binding monomer.
- [0200] SEQ ID NO: 39 sets forth the amino acid sequence of the F8R 3-4L.5 meganuclease F8R4-binding monomer.
- [0201] SEQ ID NO: 40 sets forth the amino acid sequence of the F8R 9-10x.70 meganuclease.
- [0202] SEQ ID NO: 41 sets forth the amino acid sequence of the F8R 9-10x.38 meganuclease.
- [0203] SEQ ID NO: 42 sets forth the amino acid sequence of the F8R 9-10x.2 meganuclease.
- [0204] SEQ ID NO: 43 sets forth the amino acid sequence of the F8R 9-10x.8 meganuclease.
- [0205] SEQ ID NO: 44 sets forth the amino acid sequence of the F8R 9-10x.70 meganuclease F8R9-binding monomer.
- [0206] SEQ ID NO: 45 sets forth the amino acid sequence of the F8R 9-10x.38 meganuclease F8R9-binding monomer.
- [0207] SEQ ID NO: 46 sets forth the amino acid sequence of the F8R 9-10x.2 meganuclease F8R9-binding monomer.
- [0208] SEQ ID NO: 47 sets forth the amino acid sequence of the F8R 9-10x.8 meganuclease F8R9-binding monomer.
- [0209] SEQ ID NO: 48 sets forth the amino acid sequence of the F8R 9-10x.70 meganuclease F8R10-binding monomer.

- [0210] SEQ ID NO: 49 sets forth the amino acid sequence of the F8R 9-10x.38 meganuclease F8R10-binding monomer.
- [0211] SEQ ID NO: 50 sets forth the amino acid sequence of the F8R 9-10x.2 meganuclease F8R10-binding monomer.
- [0212] SEQ ID NO: 51 sets forth the amino acid sequence of the F8R 9-10x.8 meganuclease F8R10-binding monomer.
- [0213] SEQ ID NO: 52 sets forth the amino acid sequence of the F8R 11-12x.56 meganuclease.
- [0214] SEQ ID NO: 53 sets forth the amino acid sequence of the F8R 11-12x.69 meganuclease.
- [0215] SEQ ID NO: 54 sets forth the amino acid sequence of the F8R 11-12x.66 meganuclease.
- [0216] SEQ ID NO: 55 sets forth the amino acid sequence of the F8R 11-12x.41 meganuclease.
- [0217] SEQ ID NO: 56 sets forth the amino acid sequence of the F8R 11-12x.56 meganuclease F8R11-binding monomer.
- [0218] SEQ ID NO: 57 sets forth the amino acid sequence of the F8R 11-12x.69 meganuclease F8R11-binding monomer.
- [0219] SEQ ID NO: 58 sets forth the amino acid sequence of the F8R 11-12x.66 meganuclease F8R11-binding monomer.
- [0220] SEQ ID NO: 59 sets forth the amino acid sequence of the F8R 11-12x.41 meganuclease F8R11-binding monomer.
- [0221] SEQ ID NO: 60 sets forth the amino acid sequence of the F8R 11-12x.56 meganuclease F8R12-binding monomer.
- [0222] SEQ ID NO: 61 sets forth the amino acid sequence of the F8R 11-12x.69 meganuclease F8R12-binding monomer.
- [0223] SEQ ID NO: 62 sets forth the amino acid sequence of the F8R 11-12x.66 meganuclease F8R12-binding monomer.
- [0224] SEQ ID NO: 63 sets forth the amino acid sequence of the F8R 11-12x.41 meganuclease F8R12-binding monomer.
- [0225] SEQ ID NO: 64 sets forth the amino acid sequence of the F8R 13-14x.13 meganuclease.

- [0226] SEQ ID NO: 65 sets forth the amino acid sequence of the F8R 13-14x.3 meganuclease.
- [0227] SEQ ID NO: 66 sets forth the amino acid sequence of the F8R 13-14x.1 meganuclease.
- [0228] SEQ ID NO: 67 sets forth the amino acid sequence of the F8R 13-14x.11 meganuclease.
- [0229] SEQ ID NO: 68 sets forth the amino acid sequence of the F8R 13-14x.13 meganuclease F8R13-binding monomer.
- [0230] SEQ ID NO: 69 sets forth the amino acid sequence of the F8R 13-14x.3 meganuclease F8R13-binding monomer.
- [0231] SEQ ID NO: 70 sets forth the amino acid sequence of the F8R 13-14x.1 meganuclease F8R13-binding monomer.
- [0232] SEQ ID NO: 71 sets forth the amino acid sequence of the F8R 13-14x.11 meganuclease F8R13-binding monomer.
- [0233] SEQ ID NO: 72 sets forth the amino acid sequence of the F8R 13-14x.13 meganuclease F8R14-binding monomer.
- [0234] SEQ ID NO: 73 sets forth the amino acid sequence of the F8R 13-14x.3 meganuclease F8R14-binding monomer.
- [0235] SEQ ID NO: 74 sets forth the amino acid sequence of the F8R 13-14x.1 meganuclease F8R14-binding monomer.
- [0236] SEQ ID NO: 75 sets forth the amino acid sequence of the F8R 13-14x.11 meganuclease F8R14-binding monomer.
- [0237] SEQ ID NO: 76 sets forth the amino acid sequence of the F8R 15-16x.14 meganuclease.
- [0238] SEQ ID NO: 77 sets forth the amino acid sequence of the F8R 15-16x.85 meganuclease.
- [0239] SEQ ID NO: 78 sets forth the amino acid sequence of the F8R 15-16x.4 meganuclease.
- [0240] SEQ ID NO: 79 sets forth the amino acid sequence of the F8R 15-16x.79 meganuclease.
- [0241] SEQ ID NO: 80 sets forth the amino acid sequence of the F8R 15-16x.14 meganuclease F8R15-binding monomer.

[0242] SEQ ID NO: 81 sets forth the amino acid sequence of the F8R 15-16x.85 meganuclease F8R15-binding monomer.

[0243] SEQ ID NO: 82 sets forth the amino acid sequence of the F8R 15-16x.4 meganuclease F8R15-binding monomer.

[0244] SEQ ID NO: 83 sets forth the amino acid sequence of the F8R 15-16x.79 meganuclease F8R15-binding monomer.

[0245] SEQ ID NO: 84 sets forth the amino acid sequence of the F8R 15-16x.14 meganuclease F8R16-binding monomer.

[0246] SEQ ID NO: 85 sets forth the amino acid sequence of the F8R 15-16x.85 meganuclease F8R16-binding monomer.

[0247] SEQ ID NO: 86 sets forth the amino acid sequence of the F8R 15-16x.4 meganuclease F8R16-binding monomer.

[0248] SEQ ID NO: 87 sets forth the amino acid sequence of the F8R 15-16x.79 meganuclease F8R16-binding monomer.

[0249] SEQ ID NO: 88 sets forth the nucleic acid sequence of the U1 primer.

[0250] SEQ ID NO: 89 sets forth the nucleic acid sequence of the D1 primer.

[0251] SEQ ID NO: 90 sets forth the nucleic acid sequence of the U3 primer.

[0252] SEQ ID NO: 91 sets forth the nucleic acid sequence of the FWD1 primer.

[0253] SEQ ID NO: 92 sets forth the nucleic acid sequence of the REV1 primer.

[0254] SEQ ID NO: 93 sets forth the nucleic acid sequence of the FWD3 primer.

[0255] SEQ ID NO: 94 sets forth the nucleic acid sequence of the H1U primer.

[0256] SEQ ID NO: 95 sets forth the nucleic acid sequence of the H1D primer.

[0257] SEQ ID NO: 96 sets forth the nucleic acid sequence of the H3D primer.

DETAILED DESCRIPTION OF THE INVENTION

1.1 References and Definitions

[0258] The patent and scientific literature referred to herein establishes knowledge that is available to those of skill in the art. The issued US patents, allowed applications, published foreign applications, and references, including GenBank database sequences, which are cited herein are hereby incorporated by reference to the same extent as if each was specifically and individually indicated to be incorporated by reference.

[0259] The present invention can be embodied in different forms and should not be construed as limited to the embodiments set forth herein. Rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. For example, features illustrated with respect to one embodiment can be incorporated into other embodiments, and features illustrated with respect to a particular embodiment can be deleted from that embodiment. In addition, numerous variations and additions to the embodiments suggested herein will be apparent to those skilled in the art in light of the instant disclosure, which do not depart from the instant invention.

[0260] Unless otherwise defined, all technical and scientific terms used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this invention belongs. The terminology used in the description of the invention herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the invention.

[0261] All publications, patent applications, patents, and other references mentioned herein are incorporated by reference herein in their entirety.

[0262] As used herein, “a,” “an,” or “the” can mean one or more than one. For example, “a” cell can mean a single cell or a multiplicity of cells.

[0263] As used herein, unless specifically indicated otherwise, the word “or” is used in the inclusive sense of “and/or” and not the exclusive sense of “either/or.”

[0264] As used herein, the terms “nuclease” and “endonuclease” are used interchangeably to refer to naturally-occurring or engineered enzymes which cleave a phosphodiester bond within a polynucleotide chain.

[0265] As used herein, the term “meganuclease” refers to an endonuclease that binds double-stranded DNA at a recognition sequence that is greater than 12 base pairs. Preferably, the recognition sequence for a meganuclease of the invention is 22 base pairs. A meganuclease can be an endonuclease that is derived from I-CreI, and can refer to an engineered variant of I-CreI that has been modified relative to natural I-CreI with respect to, for example, DNA-binding specificity, DNA cleavage activity, DNA-binding affinity, or dimerization properties. Methods for producing such modified variants of I-CreI are known in the art (*e.g.* WO 2007/047859). A meganuclease as used herein binds to double-stranded DNA as a heterodimer. A meganuclease may also be a “single-chain meganuclease” in which a pair of DNA-binding domains are joined into a single polypeptide using a peptide

linker. The term “homing endonuclease” is synonymous with the term “meganuclease.” Meganucleases of the invention are substantially non-toxic when expressed in cells without observing deleterious effects on cell viability or significant reductions in meganuclease cleavage activity when measured using the methods described herein.

[0266] As used herein, the term “single-chain meganuclease” refers to a polypeptide comprising a pair of nuclease subunits joined by a linker. A single-chain meganuclease has the organization: N-terminal subunit – Linker – C-terminal subunit. The two meganuclease subunits will generally be non-identical in amino acid sequence and will recognize non-identical DNA sequences. Thus, single-chain meganucleases typically cleave pseudo-palindromic or non-palindromic recognition sequences. A single-chain meganuclease may be referred to as a “single-chain heterodimer” or “single-chain heterodimeric meganuclease” although it is not, in fact, dimeric. For clarity, unless otherwise specified, the term “meganuclease” can refer to a dimeric or single-chain meganuclease.

[0267] As used herein, the term “linker” refers to an exogenous peptide sequence used to join two meganuclease subunits into a single polypeptide. A linker may have a sequence that is found in natural proteins, or may be an artificial sequence that is not found in any natural protein. A linker may be flexible and lacking in secondary structure or may have a propensity to form a specific three-dimensional structure under physiological conditions. A linker can include, without limitation, those encompassed by U.S. Patent No. 8,445,251. In some embodiments, a linker may have an amino acid sequence comprising residues 154-195 of any one of SEQ ID NOs: 19-21, 28-31, 40-43, 52-55, 64-67, or 76-79.

[0268] As used herein, the term “TALEN” refers to an endonuclease comprising a DNA-binding domain comprising 16-22 TAL domain repeats fused to any portion of the FokI nuclease domain.

[0269] As used herein, the term “Compact TALEN” refers to an endonuclease comprising a DNA-binding domain with 16-22 TAL domain repeats fused in any orientation to any portion of the I-TevI homing endonuclease.

[0270] As used herein, the term “zinc finger nuclease” or “ZFN” refers to a chimeric endonuclease comprising a zinc finger DNA-binding domain fused to the nuclease domain of the FokI restriction enzyme. The zinc finger domain can be redesigned through rational or experimental means to produce a protein which binds to a pre-determined DNA sequence ~18 basepairs in length, comprising a pair of nine basepair half-sites separated by 2-10 basepairs. Cleavage by a zinc finger nuclease can create a blunt end or a 5' overhang of

variable length (frequently four basepairs).

[0271] As used herein, the term “CRISPR” refers to a caspase-based endonuclease comprising a caspase, such as Cas9, and a guide RNA that directs DNA cleavage of the caspase by hybridizing to a recognition site in the genomic DNA.

[0272] As used herein, the term “megaTAL” refers to a single-chain endonuclease comprising a transcription activator-like effector (TALE) DNA binding domain with an engineered, sequence-specific homing endonuclease.

[0273] As used herein, with respect to a protein, the term “recombinant” or “engineered” means having an altered amino acid sequence as a result of the application of genetic engineering techniques to nucleic acids which encode the protein, and cells or organisms which express the protein. With respect to a nucleic acid, the term “recombinant” or “engineered” means having an altered nucleic acid sequence as a result of the application of genetic engineering techniques. Genetic engineering techniques include, but are not limited to, PCR and DNA cloning technologies; transfection, transformation and other gene transfer technologies; homologous recombination; site-directed mutagenesis; and gene fusion. In accordance with this definition, a protein having an amino acid sequence identical to a naturally-occurring protein, but produced by cloning and expression in a heterologous host, is not considered recombinant.

[0274] As used herein, the term “wild-type” refers to the most common naturally occurring allele (i.e., polynucleotide sequence) in the allele population of the same type of gene, wherein a polypeptide encoded by the wild-type allele has its original functions. The term “wild-type” also refers a polypeptide encoded by a wild-type allele. Wild-type alleles (i.e., polynucleotides) and polypeptides are distinguishable from mutant or variant alleles and polypeptides, which comprise one or more mutations and/or substitutions relative to the wild-type sequence(s). Whereas a wild-type allele or polypeptide can confer a normal phenotype in an organism, a mutant or variant allele or polypeptide can, in some instances, confer an altered phenotype. Wild-type nucleases are distinguishable from recombinant or non-naturally-occurring nucleases. The term “wild-type” can also refer to a cell, an organism, and/or a subject which possesses a wild-type allele of a particular gene, or a cell, an organism, and/or a subject used for comparative purposes.

[0275] As used herein, the term “genetically-modified” refers to a cell or organism in which, or in an ancestor of which, a genomic DNA sequence has been deliberately modified

by recombinant technology. As used herein, the term “genetically-modified” encompasses the term “transgenic.”

[0276] As used herein with respect to recombinant proteins, the term “modification” means any insertion, deletion, or substitution of an amino acid residue in the recombinant sequence relative to a reference sequence (*e.g.*, a wild-type or a native sequence).

[0277] As used herein, the term “recognition sequence” refers to a DNA sequence that is bound and cleaved by an endonuclease. In the case of a meganuclease, a recognition sequence comprises a pair of inverted, 9 basepair “half sites” which are separated by four basepairs. In the case of a single-chain meganuclease, the N-terminal domain of the protein contacts a first half-site and the C-terminal domain of the protein contacts a second half-site. Cleavage by a meganuclease produces four basepair 3' “overhangs”. “Overhangs”, or “sticky ends” are short, single-stranded DNA segments that can be produced by endonuclease cleavage of a double-stranded DNA sequence. In the case of meganucleases and single-chain meganucleases derived from I-CreI, the overhang comprises bases 10-13 of the 22 basepair recognition sequence. In the case of a Compact TALEN, the recognition sequence comprises a first CNNNGN sequence that is recognized by the I-TevI domain, followed by a non-specific spacer 4-16 basepairs in length, followed by a second sequence 16-22 bp in length that is recognized by the TAL-effector domain (this sequence typically has a 5' T base). Cleavage by a Compact TALEN produces two basepair 3' overhangs. In the case of a CRISPR, the recognition sequence is the sequence, typically 16-24 basepairs, to which the guide RNA binds to direct Cas9 cleavage. Cleavage by a CRISPR produced blunt ends. In the case of a zinc finger, the DNA binding domains typically recognize an 18-bp recognition sequence comprising a pair of nine basepair “half-sites” separated by 2-10 basepairs and cleavage by the nuclease creates a blunt end or a 5' overhang of variable length (frequently four basepairs).

[0278] As used herein, the term “target site” or “target sequence” refers to a region of the chromosomal DNA of a cell comprising a recognition sequence for a nuclease.

[0279] As used herein, the term “DNA-binding affinity” or “binding affinity” means the tendency of a meganuclease to non-covalently associate with a reference DNA molecule (*e.g.*, a recognition sequence or an arbitrary sequence). Binding affinity is measured by a dissociation constant, K_d . As used herein, a nuclease has “altered” binding affinity if the K_d of the nuclease for a reference recognition sequence is increased or decreased by a statistically significant ($p < 0.05$) amount relative to a reference nuclease.

[0280] As used herein, the term “specificity” means the ability of a meganuclease to recognize and cleave double-stranded DNA molecules only at a particular sequence of base pairs referred to as the recognition sequence, or only at a particular set of recognition sequences. The set of recognition sequences will share certain conserved positions or sequence motifs, but may be degenerate at one or more positions. A highly-specific meganuclease is capable of cleaving only one or a very few recognition sequences. Specificity can be determined by any method known in the art. As used herein, a meganuclease has “altered” specificity if it binds to and cleaves a recognition sequence which is not bound to and cleaved by a reference meganuclease (*e.g.*, a wild-type) under physiological conditions, or if the rate of cleavage of a recognition sequence is increased or decreased by a biologically significant amount (*e.g.*, at least 2×, or 2×-10×) relative to a reference meganuclease.

[0281] As used herein, the term “homologous recombination” or “HR” refers to the natural, cellular process in which a double-stranded DNA-break is repaired using a homologous DNA sequence as the repair template (see, *e.g.* Cahill *et al.* (2006), *Front. Biosci.* 11:1958-1976). The homologous DNA sequence may be an endogenous chromosomal sequence or an exogenous nucleic acid that was delivered to the cell.

[0282] As used herein, the term “non-homologous end-joining” or “NHEJ” refers to the natural, cellular process in which a double-stranded DNA-break is repaired by the direct joining of two non-homologous DNA segments (see, *e.g.* Cahill *et al.* (2006), *Front. Biosci.* 11:1958-1976). DNA repair by non-homologous end-joining is error-prone and frequently results in the untemplated addition or deletion of DNA sequences at the site of repair. In some instances, cleavage at a target recognition sequence results in NHEJ at a target recognition site. Nuclease-induced cleavage of a target site in the coding sequence of a gene followed by DNA repair by NHEJ can introduce mutations into the coding sequence, such as frameshift mutations, that disrupt gene function. Thus, engineered nucleases can be used to effectively knock-out a gene in a population of cells.

[0283] As used herein with respect to both amino acid sequences and nucleic acid sequences, the terms “percent identity,” “sequence identity,” “percentage similarity,” “sequence similarity” and the like refer to a measure of the degree of similarity of two sequences based upon an alignment of the sequences which maximizes similarity between aligned amino acid residues or nucleotides, and which is a function of the number of identical or similar residues or nucleotides, the number of total residues or nucleotides, and the

presence and length of gaps in the sequence alignment. A variety of algorithms and computer programs are available for determining sequence similarity using standard parameters. As used herein, sequence similarity is measured using the BLASTp program for amino acid sequences and the BLASTn program for nucleic acid sequences, both of which are available through the National Center for Biotechnology Information (www.ncbi.nlm.nih.gov/), and are described in, for example, Altschul et al. (1990), J. Mol. Biol. 215:403-410; Gish and States (1993), Nature Genet. 3:266-272; Madden et al. (1996), Meth. Enzymol. 266:131-141; Altschul et al. (1997), Nucleic Acids Res. 25:33 89-3402; Zhang et al. (2000), J. Comput. Biol. 7(1-2):203-14. As used herein, percent similarity of two amino acid sequences is the score based upon the following parameters for the BLASTp algorithm: word size=3; gap opening penalty=-11; gap extension penalty=-1; and scoring matrix=BLOSUM62. As used herein, percent similarity of two nucleic acid sequences is the score based upon the following parameters for the BLASTn algorithm: word size=11; gap opening penalty=-5; gap extension penalty=-2; match reward=1; and mismatch penalty=-3.

[0284] As used herein with respect to modifications of two proteins or amino acid sequences, the term “corresponding to” is used to indicate that a specified modification in the first protein is a substitution of the same amino acid residue as in the modification in the second protein, and that the amino acid position of the modification in the first proteins corresponds to or aligns with the amino acid position of the modification in the second protein when the two proteins are subjected to standard sequence alignments (e.g., using the BLASTp program). Thus, the modification of residue “X” to amino acid “A” in the first protein will correspond to the modification of residue “Y” to amino acid “A” in the second protein if residues X and Y correspond to each other in a sequence alignment, and despite the fact that X and Y may be different numbers.

[0285] As used herein, the term “recognition half-site,” “recognition sequence half-site,” or simply “half-site” means a nucleic acid sequence in a double-stranded DNA molecule which is recognized by a monomer of a homodimeric or heterodimeric meganuclease, or by one subunit of a single-chain meganuclease.

[0286] As used herein, the term “hypervariable region” refers to a localized sequence within a meganuclease monomer or subunit that comprises amino acids with relatively high variability. A hypervariable region can comprise about 50-60 contiguous residues, about 53-57 contiguous residues, or preferably about 56 residues. In some embodiments, the residues of a hypervariable region may correspond to positions 24-79 or positions 215-270 of any one

of SEQ ID NOs: 19-21, 28-31, 40-43, 52-55, 64-67, or 76-79. A hypervariable region can comprise one or more residues that contact DNA bases in a recognition sequence and can be modified to alter base preference of the monomer or subunit. A hypervariable region can also comprise one or more residues that bind to the DNA backbone when the meganuclease associates with a double-stranded DNA recognition sequence. Such residues can be modified to alter the binding affinity of the meganuclease for the DNA backbone and the target recognition sequence. In different embodiments of the invention, a hypervariable region may comprise between 1-20 residues that exhibit variability and can be modified to influence base preference and/or DNA-binding affinity. In particular embodiments, a hypervariable region comprises between about 15-18 residues that exhibit variability and can be modified to influence base preference and/or DNA-binding affinity. In some embodiments, variable residues within a hypervariable region correspond to one or more of positions 24, 26, 28, 30, 32, 33, 38, 40, 42, 44, 46, 68, 70, 72, 73, 75, and 77 of any one of SEQ ID NOs: 19-21, 28-31, 40-43, 52-55, 64-67, or 76-79. In other embodiments, variable residues within a hypervariable region correspond to one or more of positions 215, 217, 219, 221, 223, 224, 229, 231, 233, 235, 237, 259, 261, 263, 264, 266, and 268 of any one of SEQ ID NOs: 19-21, 28-31, 40-43, 52-55, 64-67, or 76-79.

[0287] As used herein, the terms “Factor VIII gene,” “F8 gene,” and the like, refer to a gene located on the X chromosome which encodes the coagulation Factor VIII protein. In humans, the Factor VIII gene, identified by NCBI as Gene ID No. 2157, is located from base pair 154,835,788 to base pair 155,026,934 on the X chromosome. In canines, the Factor VIII gene can be the gene identified by NCBI Reference Sequence: NM_001003212.1. It is understood that the term “Factor VIII gene” can include both a wild-type Factor VIII gene and a Factor VIII gene which comprises naturally-occurring polymorphisms and/or mutations that allow for the production of a functional Factor VIII protein.

[0288] As used herein, the terms “int22h-1” and “int22h-1 sequence” refer to a sequence positioned within intron 22 of the Factor VIII gene having a size of approximately 9.5 kb (Bagnall et al. (2006) Journal of Thrombosis and Haemostasis 4:591-598) and can further refer to the human sequence identified by GenBank as Accession No. AY619999.1. The int22h-1 sequence is characterized as comprising a CpG island, a coding sequence for the H2AFB1 histone protein, and a coding sequence for the Factor VIII-Associated 1 protein (F8A1; also referred to as the intron 22 protein). The int22h-1 sequence is further characterized as being identical to, or having high homology with, at least one repeat

sequence that is positioned telomeric to the Factor VIII gene on the X chromosome. In humans, two repeat sequences, referred to as int22h-2 and int22h-3, are positioned telomeric to the Factor VIII gene on the X chromosome. In particular embodiments of the invention, the human int22h-1 sequence can comprise SEQ ID NO: 3. In other particular embodiments of the invention, the canine int22h-1 sequence can comprise SEQ ID NO: 4.

[0289] As used herein, the terms “F8A1 coding sequence” and “intron 22 protein coding sequence” are used interchangeably and refer to a sequence positioned within the int22h-1 sequence which encodes the F8A1 protein. The F8A1 coding sequence is intronless and is transcribed in the opposite direction as the Factor VIII gene. In one embodiment, the wild-type human F8A1 coding sequence can comprise SEQ ID NO: 5. In another embodiment, the wild-type canine F8A1 coding sequence can comprise SEQ ID NO: 6, which has ~75% homology to the human F8A1 coding sequence. It is understood that reference to an F8A1 coding sequence includes a wild-type F8A1 sequence and an F8A1 sequence comprising naturally-occurring polymorphisms and/or mutations that allow for the production of a functional F8A1 protein.

[0290] As used herein, the terms “inversion” and “inversion of exons 1-22” refer to a mutation of a Factor VIII gene wherein an intra-chromosomal homologous recombination event occurs between the int22h-1 sequence of the Factor VIII gene and an identical or closely related, inversely oriented, repeat sequence positioned telomeric to the Factor VIII gene on the X chromosome, which results in an inversion of exons 1-22 with respect to exons 23-26.

[0291] As used herein, the term “reversion” refers to an intra-chromosomal homologous recombination event in a cell comprising an inversion of exons 1-22 of the Factor VIII gene, wherein a double-strand break is produced within the int22h-1 sequence to promote recombination with a repeat sequence telomeric to the Factor VIII gene on the X chromosome. Such recombination results in the corrected orientation of exons 1-22 and the production of a functional, wild-type Factor VIII gene.

[0292] The terms “recombinant DNA construct,” “recombinant construct,” “expression cassette,” “expression construct,” “chimeric construct,” “construct,” and “recombinant DNA fragment” are used interchangeably herein and are nucleic acid fragments. A recombinant construct comprises an artificial combination of nucleic acid fragments, including, without limitation, regulatory and coding sequences that are not found together in nature. For example, a recombinant DNA construct may comprise regulatory sequences and coding

sequences that are derived from different sources, or regulatory sequences and coding sequences derived from the same source and arranged in a manner different than that found in nature. Such a construct may be used by itself or may be used in conjunction with a vector.

[0293] As used herein, a “vector” or “recombinant DNA vector” may be a construct that includes a replication system and sequences that are capable of transcription and translation of a polypeptide-encoding sequence in a given host cell. If a vector is used then the choice of vector is dependent upon the method that will be used to transform host cells as is well known to those skilled in the art. Vectors can include, without limitation, plasmid vectors and recombinant AAV vectors, or any other vector known in that art suitable for delivering a gene encoding a meganuclease of the invention to a target cell. The skilled artisan is well aware of the genetic elements that must be present on the vector in order to successfully transform, select and propagate host cells comprising any of the isolated nucleotides or nucleic acid sequences of the invention.

[0294] As used herein, a “vector” can also refer to a viral vector. Viral vectors can include, without limitation, retroviral vectors, lentiviral vectors, adenoviral vectors, and adeno-associated viral vectors (AAV).

[0295] As used herein, a “control” or “control cell” refers to a cell that provides a reference point for measuring changes in genotype or phenotype of a genetically-modified cell. A control cell may comprise, for example: (a) a wild-type cell, i.e., of the same genotype as the starting material for the genetic alteration which resulted in the genetically-modified cell; (b) a cell of the same genotype as the genetically-modified cell but which has been transformed with a null construct (i.e., with a construct which has no known effect on the trait of interest); or, (c) a cell genetically identical to the genetically-modified cell but which is not exposed to conditions or stimuli or further genetic modifications that would induce expression of altered genotype or phenotype.

[0296] As used herein, a “self-cleaving” recombinant DNA construct refers to a DNA construct which comprises at least one coding sequence for an endonuclease and at least one recognition sequence for the same endonuclease. When expressed in a cell (i.e., in vivo), the endonuclease recognizes and cleaves the recognition sequence, resulting in linearization of the DNA construct.

[0297] As used herein with respect to modifications of two proteins or amino acid sequences, the term “corresponding to” is used to indicate that a specified modification in the first protein is a substitution of the same amino acid residue as in the modification in the

second protein, and that the amino acid position of the modification in the first proteins corresponds to or aligns with the amino acid position of the modification in the second protein when the two proteins are subjected to standard sequence alignments (e.g., using the BLASTp program). Thus, the modification of residue “X” to amino acid “A” in the first protein will correspond to the modification of residue “Y” to amino acid “A” in the second protein if residues X and Y correspond to each other in a sequence alignment, and despite the fact that X and Y may be different numbers.

[0298] As used herein, the terms “treatment” or “treating a subject” refers to the administration of an engineered nuclease of the invention, or a nucleic acid encoding an engineered nuclease of the invention, to a subject having hemophilia A for the purpose of correcting an inversion of exons 1-22 in the Factor VIII gene in cells which normally express Factor VIII in wild-type subjects. Such treatment results in correction of the Factor VIII gene in a number of cells sufficient to increase circulating levels of Factor VIII in the subject, and either partial or complete relief of one or more symptoms of hemophilia A in the subject. The terms “treatment” or “treating a subject” can further refer to the administration of a genetically-modified cell comprising a wild-type Factor VIII gene to a subject according the method of the invention, wherein the genetically-modified cell is delivered to a target tissue and either produces Factor VIII, or differentiates into a cell which produces Factor VIII, in an amount sufficient to increase the circulating levels of Factor VIII in the subject, resulting in either partial or complete relief of one or more symptoms of hemophilia A. In some aspects, an engineered nuclease of the invention, a nucleic acid encoding the same, or a genetically-modified cell of the invention is administered during treatment in the form of a pharmaceutical composition of the invention.

[0299] As used herein, the recitation of a numerical range for a variable is intended to convey that the invention may be practiced with the variable equal to any of the values within that range. Thus, for a variable which is inherently discrete, the variable can be equal to any integer value within the numerical range, including the end-points of the range. Similarly, for a variable which is inherently continuous, the variable can be equal to any real value within the numerical range, including the end-points of the range. As an example, and without limitation, a variable which is described as having values between 0 and 2 can take the values 0, 1 or 2 if the variable is inherently discrete, and can take the values 0.0, 0.1, 0.01, 0.001, or any other real values $\square 0$ and $\square 2$ if the variable is inherently continuous.

2.1 Principle of the Invention

[0300] The present invention is based, in part, on the hypothesis that engineered nucleases can be used to treat hemophilia A by correcting an inversion of exons 1-22 in the Factor VIII gene. More specifically, nucleases can be engineered to recognize and cleave a recognition sequence present within an int22h-1 sequence of the Factor VIII gene to produce a double-strand break. Intra-chromosomal homologous recombination can then occur between the int22h-1 sequence and a repeat sequence which is telomeric to the Factor VIII gene on the X chromosome, resulting in a reversion of exons 1-22 and the production of a functional, wild-type Factor VIII gene in target cells of the subject.

[0301] The invention is also based, in part, on the hypothesis that pluripotent cells (*e.g.*, induced pluripotent stem (iPS) cells) comprising an inversion of exons 1-22 in the Factor VIII gene can be obtained and contacted with an engineered nuclease of the invention (or a nucleic acid encoding the same) in order to correct the Factor VIII gene by the same mechanism described above. Such pluripotent cells can then be administered to a subject having hemophilia A, wherein the cells are delivered to a target tissue (*e.g.*, the liver or the circulatory system) and differentiate into cells which express wild-type Factor VIII in the subject.

[0302] Thus, the present invention encompasses engineered nucleases, and particularly engineered recombinant meganucleases, which recognize and cleave a recognition sequence within the int22h-1 sequence of a Factor VIII gene. The present invention also encompasses methods of using such engineered nucleases to make genetically-modified cells, and the use of such cells in a pharmaceutical composition and in methods for treating hemophilia A. Further, the invention encompasses pharmaceutical compositions comprising engineered nuclease proteins, nucleic acids encoding engineered nucleases, or genetically-modified cells of the invention, and the use of such compositions for the treatment of hemophilia A.

2.2 Nucleases for Recognizing and Cleaving Recognition Sequences Within an int22h-1 Sequence of the Factor VIII Gene

[0303] It is known in the art that it is possible to use a site-specific nuclease to make a DNA break in the genome of a living cell, and that such a DNA break can result in permanent modification of the genome via homologous recombination of the cleaved target site with an identical or highly homologous DNA sequence within the genome.

[0304] Thus, in different embodiments, a variety of different types of endonuclease are useful for practicing the invention. In one embodiment, the invention can be practiced using engineered recombinant meganucleases. In another embodiment, the invention can be practiced using a CRISPR nuclease or CRISPR Nickase. Methods for making CRISPRs and CRISPR Nickases that recognize pre-determined DNA sites are known in the art, for example Ran, et al. (2013) Nat Protoc. 8:2281-308. In another embodiment, the invention can be practiced using TALENs or Compact TALENs. Methods for making TALE domains that bind to pre-determined DNA sites are known in the art, for example Reyon et al. (2012) Nat Biotechnol. 30:460-5. In another embodiment, the invention can be practiced using zinc finger nucleases (ZFNs). In a further embodiment, the invention can be practiced using megaTALs.

[0305] In preferred embodiments, the nucleases used to practice the invention are single-chain meganucleases. A single-chain meganuclease comprises an N-terminal subunit and a C-terminal subunit joined by a linker peptide. Each of the two domains recognizes half of the recognition sequence (i.e., a recognition half-site) and the site of DNA cleavage is at the middle of the recognition sequence near the interface of the two subunits. DNA strand breaks are offset by four base pairs such that DNA cleavage by a meganuclease generates a pair of four base pair, 3' single-strand overhangs.

[0306] In some examples, recombinant meganucleases of the invention have been engineered to recognize and cleave the F8R 1-2 recognition sequence (SEQ ID NO: 7). The F8R 1-2 recognition sequence is positioned within both the int22h-1 sequence and the F8A1 sequence. Such recombinant meganucleases are collectively referred to herein as "F8R 1-2 meganucleases." Exemplary F8R 1-2 meganucleases are provided in SEQ ID NOs: 19-22.

[0307] In additional examples, recombinant meganucleases of the invention have been engineered to recognize and cleave the F8R 3-4 recognition sequence (SEQ ID NO: 9). The F8R 3-4 recognition sequence is positioned within both the int22h-1 sequence and the F8A1 sequence. Such recombinant meganucleases are collectively referred to herein as "F8R 3-4 meganucleases." Exemplary F8R 3-4 meganucleases are provided in SEQ ID NOs: 28-31.

[0308] In additional examples, recombinant meganucleases of the invention have been engineered to recognize and cleave the F8R 9-10 recognition sequence (SEQ ID NO: 11). Such recombinant meganucleases are collectively referred to herein as "F8R 9-10 meganucleases." Exemplary F8R 9-10 meganucleases are provided in SEQ ID NOs: 40-43.

[0309] In additional examples, recombinant meganucleases of the invention have been engineered to recognize and cleave the F8R 11-12 recognition sequence (SEQ ID NO: 13). Such recombinant meganucleases are collectively referred to herein as “F8R 11-12 meganucleases.” Exemplary F8R 11-12 meganucleases are provided in SEQ ID NOs: 52-55.

[0310] In additional examples, recombinant meganucleases of the invention have been engineered to recognize and cleave the F8R 13-14 recognition sequence (SEQ ID NO: 15). Such recombinant meganucleases are collectively referred to herein as “F8R 13-14 meganucleases.” Exemplary F8R 13-14 meganucleases are provided in SEQ ID NOs: 64-67.

[0311] In additional examples, recombinant meganucleases of the invention have been engineered to recognize and cleave the F8R 15-16 recognition sequence (SEQ ID NO: 17). Such recombinant meganucleases are collectively referred to herein as “F8R 15-16 meganucleases.” Exemplary F8R 15-16 meganucleases are provided in SEQ ID NOs: 76-79.

[0312] Recombinant meganucleases of the invention comprise a first subunit, comprising a first hypervariable (HVR1) region, and a second subunit, comprising a second hypervariable (HVR2) region. Further, the first subunit binds to a first recognition half-site in the recognition sequence (e.g., the F8R1, F8R3, F8R9, F8R11, F8R13, or F8R15 half-site), and the second subunit binds to a second recognition half-site in the recognition sequence (e.g., the F8R2, F8R4, F8R10, F8R12, F8R14, or F8R16 half-site). In embodiments where the recombinant meganuclease is a single-chain meganuclease, the first and second subunits can be oriented such that the first subunit, which comprises the HVR1 region and binds the first half-site, is positioned as the N-terminal subunit, and the second subunit, which comprises the HVR2 region and binds the second half-site, is positioned as the C-terminal subunit. In alternative embodiments, the first and second subunits can be oriented such that the first subunit, which comprises the HVR1 region and binds the first half-site, is positioned as the C-terminal subunit, and the second subunit, which comprises the HVR2 region and binds the second half-site, is positioned as the N-terminal subunit. Exemplary F8R 1-2 meganucleases of the invention are provided in Table 1. Exemplary F8R 3-4 meganucleases of the invention are provided in Table 2. Exemplary F8R 9-10 meganucleases of the invention are provided in Table 3. Exemplary F8R 11-12 meganucleases of the invention are provided in Table 4. Exemplary F8R 13-14 meganucleases of the invention are provided in Table 5. Exemplary F8R 15-16 meganucleases of the invention are provided in Table 6.

Table 1. Exemplary recombinant meganucleases engineered to recognize and cleave the F8R 1-2 recognition sequence (SEQ ID NO: 7)

Meganuclease	AA SEQ ID	F8R1 Subunit Residues	F8R1 Subunit SEQ ID	*F8R1 Subunit %	F8R2 Subunit Residues	F8R2 Subunit SEQ ID	*F8R2 Subunit %
F8R 1-2x.27	19	198-344	22	100	7-153	25	100
F8R 1-2x.15	20	7-153	23	95.24	198-344	26	95.24
F8R 1-2x.9	21	7-153	24	95.24	198-344	27	95.24

*“F8R1 Subunit %” and “F8R2 Subunit %” represent the amino acid sequence identity between the F8R1-binding and F8R2-binding subunit regions of each meganuclease and the F8R1-binding and F8R2-binding subunit regions, respectively, of the F8R 1-2x.27 meganuclease.

Table 2. Exemplary recombinant meganucleases engineered to recognize and cleave the F8R 3-4 recognition sequence (SEQ ID NO: 9)

Meganuclease	AA SEQ ID	F8R3 Subunit Residues	F8R3 Subunit SEQ ID	*F8R3 Subunit %	F8R4 Subunit Residues	F8R4 Subunit SEQ ID	*F8R4 Subunit %
F8R 3-4x.43	28	198-344	32	100	7-153	36	100
F8R 3-4x.70	29	198-344	33	98.64	7-153	37	91.16
F8R 3-4x.4	30	198-344	34	100	7-153	38	98.64
F8R 3-4L.5	31	198-344	35	98.64	7-153	39	97.28

*“F8R3 Subunit %” and “F8R4 Subunit %” represent the amino acid sequence identity between the F8R3-binding and F8R4-binding subunit regions of each meganuclease and the F8R3-binding and F8R4-binding subunit regions, respectively, of the F8R 3-4x.43 meganuclease.

Table 3. Exemplary recombinant meganucleases engineered to recognize and cleave the F8R 9-10 recognition sequence (SEQ ID NO: 11)

Meganuclease	AA SEQ ID	F8R9 Subunit Residues	F8R9 Subunit SEQ ID	*F8R9 Subunit %	F8R10 Subunit Residues	F8R10 Subunit SEQ ID	*F8R10 Subunit %
F8R 9-10x.70	40	7-153	44	100	198-344	48	100
F8R 9-10x.38	41	198-344	45	97.96	7-153	49	100
F8R 9-10x.2	42	198-344	46	94.56	7-153	50	91.84
F8R 9-10x.8	43	198-344	47	95.24	7-153	51	98.64

*“F8R9 Subunit %” and “F8R10 Subunit %” represent the amino acid sequence identity between the F8R9-binding and F8R10-binding subunit regions of each meganuclease and the F8R9-binding and F8R10-binding subunit regions, respectively, of the F8R 9-10x.70 meganuclease.

Table 4. Exemplary recombinant meganucleases engineered to recognize and cleave the F8R 11-12 recognition sequence (SEQ ID NO: 13)

Meganuclease	AA SEQ ID	F8R11 Subunit Residues	F8R11 Subunit SEQ ID	*F8R11 Subunit %	F8R12 Subunit Residues	F8R12 Subunit SEQ ID	*F8R12 Subunit %
F8R 11-12x.56	52	7-153	56	100	198-344	60	100
F8R 11-12x.69	53	7-153	57	91.84	198-344	61	95.24
F8R 11-12x.66	54	7-153	58	92.52	198-344	62	90.48
F8R 11-12x.41	55	7-153	59	91.84	198-344	63	92.52

*“F8R11 Subunit %” and “F8R12 Subunit %” represent the amino acid sequence identity between the F8R11-binding and F8R12-binding subunit regions of each meganuclease and the F8R11-binding and F8R12-binding subunit regions, respectively, of the F8R 11-12x.56 meganuclease.

Table 5. Exemplary recombinant meganucleases engineered to recognize and cleave the F8R 13-14 recognition sequence (SEQ ID NO: 15)

Meganuclease	AA SEQ ID	F8R13 Subunit Residues	F8R13 Subunit SEQ ID	*F8R13 Subunit %	F8R14 Subunit Residues	F8R14 Subunit SEQ ID	*F8R14 Subunit %
F8R 13-14x.13	64	7-153	68	100	198-344	72	100
F8R 13-14x.3	65	198-344	69	94.56	7-153	73	92.52
F8R 13-14x.1	66	198-344	70	93.88	7-153	74	93.2
F8R 13-14x.11	67	198-344	71	93.2	7-153	75	93.2

*“F8R13 Subunit %” and “F8R14 Subunit %” represent the amino acid sequence identity between the F8R13-binding and F8R14-binding subunit regions of each meganuclease and the F8R13-binding and F8R14-binding subunit regions, respectively, of the F8R 13-14x.13 meganuclease.

Table 6. Exemplary recombinant meganucleases engineered to recognize and cleave the F8R 15-16 recognition sequence (SEQ ID NO: 17)

Meganuclease	AA SEQ ID	F8R15 Subunit Residues	F8R15 Subunit SEQ ID	*F8R15 Subunit %	F8R16 Subunit Residues	F8R16 Subunit SEQ ID	*F8R16 Subunit %
F8R 15-16x.14	76	198-344	80	100	7-153	84	100
F8R 15-16x.85	77	198-344	81	99.32	7-153	85	93.88
F8R 15-16x.4	78	198-344	82	95.24	7-153	86	91.84
F8R 15-16x.79	79	198-344	83	94.56	7-153	87	92.52

*“F8R15 Subunit %” and “F8R16 Subunit %” represent the amino acid sequence identity between the F8R15-binding and F8R16-binding subunit regions of each meganuclease and the F8R15-binding and F8R16-binding subunit regions, respectively, of the F8R 15-16x.14 meganuclease.

2.3 Methods for Delivering and Expressing Endonucleases

[0313] The invention provides methods for producing genetically-modified cells using engineered nucleases that recognize and cleave recognition sequences found within an intron 22 sequence of a Factor VIII gene. The invention further provides methods for treating hemophilia A in a subject by administering a pharmaceutical composition comprising a pharmaceutically acceptable carrier and an engineered nuclease of the invention (or a nucleic acid encoding the engineered nuclease). In each case, the invention requires that an engineered nuclease of the invention can be delivered to and/or expressed from DNA/RNA in appropriate cells that comprise an inversion of exons 1-22 in a Factor VIII gene and would typically express Factor VIII in a healthy subject (e.g., hepatic sinusoidal endothelial cells or hematopoietic endothelial cells, or progenitor cells which differentiate into the same).

[0314] Engineered nucleases of the invention can be delivered into a cell in the form of protein or, preferably, as a nucleic acid encoding the engineered nuclease. Such nucleic acid can be DNA (e.g., circular or linearized plasmid DNA or PCR products) or RNA (e.g., mRNA). For embodiments in which the engineered nuclease coding sequence is delivered in DNA form, it should be operably linked to a promoter to facilitate transcription of the nuclease gene. Mammalian promoters suitable for the invention include constitutive promoters such as the cytomegalovirus early (CMV) promoter (Thomsen et al. (1984), Proc Natl Acad Sci USA. 81(3):659-63) or the SV40 early promoter (Benoist and Chambon (1981), Nature. 290(5804):304-10) as well as inducible promoters such as the tetracycline-inducible promoter (Dingermann et al. (1992), Mol Cell Biol. 12(9):4038-45). An engineered nuclease of the invention can also be operably linked to a synthetic promoter. Synthetic promoters can include, without limitation, the JeT promoter (WO 2002/012514).

[0315] In some embodiments, mRNA encoding an endonuclease is delivered to a cell because this reduces the likelihood that the gene encoding the engineered nuclease will integrate into the genome of the cell. Such mRNA encoding an engineered nuclease can be produced using methods known in the art such as in vitro transcription. In some embodiments, the mRNA is capped using 7-methyl-guanosine. In some embodiments, the mRNA may be polyadenylated.

[0316] In another particular embodiment, a nucleic acid encoding an endonuclease of the invention can be introduced into the cell using a single-stranded DNA template. The single-stranded DNA can further comprise a 5' and/or a 3' AAV inverted terminal repeat (ITR)

upstream and/or downstream of the sequence encoding the engineered nuclease. In other embodiments, the single-stranded DNA can further comprise a 5' and/or a 3' homology arm upstream and/or downstream of the sequence encoding the engineered nuclease.

[0317] In another particular embodiment, genes encoding an endonuclease of the invention can be introduced into a cell using a linearized DNA template. In some examples, a plasmid DNA encoding an endonuclease can be digested by one or more restriction enzymes such that the circular plasmid DNA is linearized prior to being introduced into a cell.

[0318] In another particular embodiment, genes encoding an endonuclease of the invention can be introduced into a cell on a self-cleaving recombinant DNA construct. Such a construct can comprise at least one coding sequence for an endonuclease and at least one recognition sequence for the same endonuclease. When expressed in a cell (i.e., in vivo), the endonuclease recognizes and cleaves the recognition sequence, resulting in linearization of the DNA construct.

[0319] Purified nuclease proteins can be delivered into cells to cleave genomic DNA by a variety of different mechanisms known in the art, including those further detailed herein below.

[0320] The target tissue(s) for delivery of recombinant meganucleases of the invention include, without limitation, cells of the liver, preferably hepatic sinusoidal endothelial cells or, alternatively, progenitor cells which differentiate into hepatic sinusoidal endothelial cells. Target tissues can also include, without limitation, cells in the circulatory system, preferably hematopoietic endothelial cells or, alternatively, progenitor cells which differentiate into hematopoietic endothelial cells. As discussed, endonucleases of the invention can be delivered as purified protein or as RNA or DNA encoding the endonucleases. In one embodiment, endonuclease proteins, or mRNA, or DNA vectors encoding endonucleases, are supplied to target cells (e.g., cells in the liver or cells in the circulatory system) via injection directly to the target tissue. Alternatively, endonuclease protein, mRNA, or DNA can be delivered systemically via the circulatory system.

[0321] In some embodiments, endonuclease proteins, or DNA/mRNA encoding endonucleases, are formulated for systemic administration, or administration to target tissues, in a pharmaceutically acceptable carrier in accordance with known techniques. See, e.g., Remington, *The Science And Practice of Pharmacy* (21st ed. 2005). In the manufacture of a pharmaceutical formulation according to the invention, proteins/RNA/mRNA are typically

admixed with a pharmaceutically acceptable carrier. The carrier must, of course, be acceptable in the sense of being compatible with any other ingredients in the formulation and must not be deleterious to the patient. The carrier can be a solid or a liquid, or both, and can be formulated with the compound as a unit-dose formulation.

[0322] In some embodiments, endonuclease proteins, or DNA/mRNA encoding the endonuclease, are coupled to a cell penetrating peptide or targeting ligand to facilitate cellular uptake. Examples of cell penetrating peptides known in the art include poly-arginine (Jearawiriyapaisarn, et al. (2008) *Mol Ther.* 16:1624-9), TAT peptide from the HIV virus (Hudecz et al. (2005), *Med. Res. Rev.* 25: 679-736), MPG (Simeoni, et al. (2003) *Nucleic Acids Res.* 31:2717-2724), Pep-1 (Deshayes et al. (2004) *Biochemistry* 43: 7698-7706, and HSV-1 VP-22 (Deshayes et al. (2005) *Cell Mol Life Sci.* 62:1839-49. In an alternative embodiment, endonuclease proteins, or DNA/mRNA encoding endonucleases, are coupled covalently or non-covalently to an antibody that recognizes a specific cell-surface receptor expressed on target cells such that the endonuclease protein/DNA/mRNA binds to and is internalized by the target cells. Alternatively, endonuclease protein/DNA/mRNA can be coupled covalently or non-covalently to the natural ligand (or a portion of the natural ligand) for such a cell-surface receptor. (McCall, et al. (2014) *Tissue Barriers.* 2(4):e944449; Dinda, et al. (2013) *Curr Pharm Biotechnol.* 14:1264-74; Kang, et al. (2014) *Curr Pharm Biotechnol.* 15(3):220-30; Qian et al. (2014) *Expert Opin Drug Metab Toxicol.* 10(11):1491-508).

[0323] In some embodiments, endonuclease proteins, or DNA/mRNA encoding endonucleases, are encapsulated within biodegradable hydrogels for injection or implantation within the desired region of the liver (e.g., in proximity to hepatic sinusoidal endothelial cells or hematopoietic endothelial cells, or progenitor cells which differentiate into the same). Hydrogels can provide sustained and tunable release of the therapeutic payload to the desired region of the target tissue without the need for frequent injections, and stimuli-responsive materials (e.g., temperature- and pH-responsive hydrogels) can be designed to release the payload in response to environmental or externally applied cues (Kang Derwent et al. (2008) *Trans Am Ophthalmol Soc.* 106:206-214).

[0324] In some embodiments, endonuclease proteins, or DNA/mRNA encoding endonucleases, are coupled covalently or, preferably, non-covalently to a nanoparticle or encapsulated within such a nanoparticle using methods known in the art (Sharma, et al. (2014) *Biomed Res Int.* 2014). A nanoparticle is a nanoscale delivery system whose length scale is <1 μm , preferably <100 nm. Such nanoparticles may be designed using a core

composed of metal, lipid, polymer, or biological macromolecule, and multiple copies of the endonuclease proteins, mRNA, or DNA can be attached to or encapsulated with the nanoparticle core. This increases the copy number of the protein/mRNA/DNA that is delivered to each cell and, so, increases the intracellular expression of each endonuclease to maximize the likelihood that the target recognition sequences will be cut. The surface of such nanoparticles may be further modified with polymers or lipids (e.g., chitosan, cationic polymers, or cationic lipids) to form a core-shell nanoparticle whose surface confers additional functionalities to enhance cellular delivery and uptake of the payload (Jian et al. (2012) *Biomaterials*. 33(30): 7621-30). Nanoparticles may additionally be advantageously coupled to targeting molecules to direct the nanoparticle to the appropriate cell type and/or increase the likelihood of cellular uptake. Examples of such targeting molecules include antibodies specific for cell-surface receptors and the natural ligands (or portions of the natural ligands) for cell surface receptors.

[0325] In some embodiments, the endonuclease proteins or DNA/mRNA encoding the endonucleases are encapsulated within liposomes or complexed using cationic lipids (see, e.g., Lipofectamine™, Life Technologies Corp., Carlsbad, CA; Zuris et al. (2015) *Nat Biotechnol*. 33: 73-80; Mishra et al. (2011) *J Drug Deliv*. 2011:863734). The liposome and lipoplex formulations can protect the payload from degradation, enhance accumulation and retention at the target site, and facilitate cellular uptake and delivery efficiency through fusion with and/or disruption of the cellular membranes of the target cells.

[0326] In some embodiments, endonuclease proteins, or DNA/mRNA encoding endonucleases, are encapsulated within polymeric scaffolds (e.g., PLGA) or complexed using cationic polymers (e.g., PEI, PLL) (Tamboli et al. (2011) *Ther Deliv*. 2(4): 523-536). Polymeric carriers can be designed to provide tunable drug release rates through control of polymer erosion and drug diffusion, and high drug encapsulation efficiencies can offer protection of the therapeutic payload until intracellular delivery to the desired target cell population.

[0327] In some embodiments, endonuclease proteins, or DNA/mRNA encoding recombinant meganucleases, are combined with amphiphilic molecules that self-assemble into micelles (Tong et al. (2007) *J Gene Med*. 9(11): 956-66). Polymeric micelles may include a micellar shell formed with a hydrophilic polymer (e.g., polyethyleneglycol) that can prevent aggregation, mask charge interactions, and reduce nonspecific interactions.

[0328] In some embodiments, endonuclease proteins, or DNA/mRNA encoding endonucleases, are formulated into an emulsion or a nanoemulsion (i.e., having an average particle diameter of < 1 nm) for administration and/or delivery to the target cell. The term “emulsion” refers to, without limitation, any oil-in-water, water-in-oil, water-in-oil-in-water, or oil-in-water-in-oil dispersions or droplets, including lipid structures that can form as a result of hydrophobic forces that drive apolar residues (e.g., long hydrocarbon chains) away from water and polar head groups toward water, when a water immiscible phase is mixed with an aqueous phase. These other lipid structures include, but are not limited to, unilamellar, paucilamellar, and multilamellar lipid vesicles, micelles, and lamellar phases. Emulsions are composed of an aqueous phase and a lipophilic phase (typically containing an oil and an organic solvent). Emulsions also frequently contain one or more surfactants. Nanoemulsion formulations are well known, e.g., as described in US Patent Application Nos. 2002/0045667 and 2004/0043041, and US Pat. Nos. 6,015,832, 6,506,803, 6,635,676, and 6,559,189, each of which is incorporated herein by reference in its entirety.

[0329] In some embodiments, endonuclease proteins, or DNA/mRNA encoding endonucleases, are covalently attached to, or non-covalently associated with, multifunctional polymer conjugates, DNA dendrimers, and polymeric dendrimers (Mastorakos et al. (2015) *Nanoscale*. 7(9): 3845-56; Cheng et al. (2008) *J Pharm Sci*. 97(1): 123-43). The dendrimer generation can control the payload capacity and size, and can provide a high drug payload capacity. Moreover, display of multiple surface groups can be leveraged to improve stability, reduce nonspecific interactions, and enhance cell-specific targeting and drug release.

[0330] In some embodiments, genes encoding an endonuclease are delivered using a viral vector. Such vectors are known in the art and include retroviral vectors, lentiviral vectors, adenoviral vectors, and adeno-associated virus (AAV) vectors (reviewed in Vannucci, et al. (2013 *New Microbiol*. 36:1-22). In some embodiments, the viral vectors are injected directly into target tissues. In alternative embodiments, the viral vectors are delivered systemically via the circulatory system. It is known in the art that different AAV vectors tend to localize to different tissues. In liver target tissues, effective transduction of hepatocytes has been shown, for example, with AAV serotypes 2, 8, and 9 (Sands (2011) *Methods Mol. Biol*. 807:141-157). AAV vectors can also be self-complementary such that they do not require second-strand DNA synthesis in the host cell (McCarty, et al. (2001) *Gene Ther*. 8:1248-54).

[0331] In one embodiment, a viral vector used for endonuclease gene delivery is a self-limiting viral vector. A self-limiting viral vector can have limited persistence time in a cell or

organism due to the presence of a recognition sequence for a recombinant meganuclease within the vector. Thus, a self-limiting viral vector can be engineered to provide coding for a promoter, an endonuclease described herein, and an endonuclease recognition site within the ITRs. The self-limiting viral vector delivers the endonuclease gene to a cell, tissue, or organism, such that the endonuclease is expressed and able to cut the genome of the cell at an endogenous recognition sequence within the genome. The delivered endonuclease will also find its target site within the self-limiting viral vector itself, and cut the vector at this target site. Once cut, the 5' and 3' ends of the viral genome will be exposed and degraded by exonucleases, thus killing the virus and ceasing production of the endonuclease.

[0332] If the endonuclease genes are delivered in DNA form (e.g. plasmid) and/or via a viral vector (e.g. AAV) they must be operably linked to a promoter. In some embodiments, this can be a viral promoter such as endogenous promoters from the viral vector (e.g. the LTR of a lentiviral vector) or the well-known cytomegalovirus- or SV40 virus-early promoters. In a preferred embodiment, meganuclease genes are operably linked to a promoter that drives gene expression preferentially in the target cells. Examples of liver-specific promoters include, without limitation, human alpha-1 antitrypsin promoter and apolipoprotein A-II promoter.

[0333] It is envisioned that a single treatment will permanently cause a reversion of exons 1-22 in the Factor VIII gene, resulting in a functional, wild-type gene in a percentage of patient target cells. If the frequency of reversion is low, however, or if a large percentage of target cells need to be corrected, it may be necessary to perform multiple treatments on each patient.

2.4 Pharmaceutical Compositions

[0334] In some embodiments, the invention provides a pharmaceutical composition comprising a pharmaceutically acceptable carrier and engineered nuclease of the invention, or a pharmaceutically acceptable carrier and an isolated polynucleotide comprising a nucleic acid encoding an engineered nuclease of the invention. In other embodiments, the invention provides a pharmaceutical composition comprising a pharmaceutically acceptable carrier and a genetically-modified cell of the invention which can be delivered to a target tissue where the cell can then differentiate into a cell which expresses wild-type Factor VIII. Pharmaceutical compositions of the invention can be useful for treating a subject having

hemophilia A, wherein the disease is characterized by an inversion of exons 1-22 in a Factor VIII gene.

[0335] Such pharmaceutical compositions can be prepared in accordance with known techniques. See, e.g., Remington, *The Science and Practice of Pharmacy* (21st ed. 2005). In the manufacture of a pharmaceutical formulation according to the invention, endonuclease polypeptides (or DNA/RNA encoding the same) are typically admixed with a pharmaceutically acceptable carrier and the resulting composition is administered to a subject. The carrier must, of course, be acceptable in the sense of being compatible with any other ingredients in the formulation and must not be deleterious to the subject. In some embodiments, pharmaceutical compositions of the invention can further comprise one or more additional agents or biological molecules useful in the treatment of a disease in the subject. Likewise, the additional agent(s) and/or biological molecule(s) can be co-administered as a separate composition.

2.5 Methods for Producing Recombinant AAV Vectors

[0336] In some embodiments, the invention provides recombinant AAV vectors for use in the methods of the invention. Recombinant AAV vectors are typically produced in mammalian cell lines such as HEK-293. Because the viral cap and rep genes are removed from the vector to prevent its self-replication to make room for the therapeutic gene(s) to be delivered (e.g. the endonuclease gene), it is necessary to provide these in trans in the packaging cell line. In addition, it is necessary to provide the “helper” (e.g. adenoviral) components necessary to support replication (Cots D, Bosch A, Chillon M (2013) *Curr. Gene Ther.* 13(5): 370-81). Frequently, recombinant AAV vectors are produced using a triple-transfection in which a cell line is transfected with a first plasmid encoding the “helper” components, a second plasmid comprising the cap and rep genes, and a third plasmid comprising the viral ITRs containing the intervening DNA sequence to be packaged into the virus. Viral particles comprising a genome (ITRs and intervening gene(s) of interest) encased in a capsid are then isolated from cells by freeze-thaw cycles, sonication, detergent, or other means known in the art. Particles are then purified using cesium-chloride density gradient centrifugation or affinity chromatography and subsequently delivered to the gene(s) of interest to cells, tissues, or an organism such as a human patient.

[0337] Because recombinant AAV particles are typically produced (manufactured) in cells, precautions must be taken in practicing the current invention to ensure that the site-specific endonuclease is not expressed in the packaging cells. Because the viral genomes of the invention comprise a recognition sequence for the endonuclease, any endonuclease expressed in the packaging cell line will be capable of cleaving the viral genome before it can be packaged into viral particles. This will result in reduced packaging efficiency and/or the packaging of fragmented genomes. Several approaches can be used to prevent endonuclease expression in the packaging cells, including:

1. The endonuclease can be placed under the control of a tissue-specific promoter that is not active in the packaging cells. For example, if a viral vector is developed for delivery of (an) endonuclease gene(s) to muscle tissue, a muscle-specific promoter can be used. Examples of muscle-specific promoters include C5-12 (Liu, *et al.* (2004) *Hum Gene Ther.* 15:783-92), the muscle-specific creatine kinase (MCK) promoter (Yuasa, *et al.* (2002) *Gene Ther.* 9:1576-88), or the smooth muscle 22 (SM22) promoter (Haase, *et al.* (2013) *BMC Biotechnol.* 13:49-54). Examples of CNS (neuron)-specific promoters include the NSE, Synapsin, and MeCP2 promoters (Lentz, *et al.* (2012) *Neurobiol Dis.* 48:179-88). Examples of liver-specific promoters include albumin promoters (such as Palb), human α 1-antitrypsin (such as Pa1AT), and hemopexin (such as Phpx) (Kramer, MG *et al.*, (2003) *Mol. Therapy* 7:375-85). Examples of eye-specific promoters include opsin, and corneal epithelium-specific K12 promoters (Martin KRG, Klein RL, and Quigley HA (2002) *Methods* (28): 267-75) (Tong Y, *et al.*, (2007) *J Gene Med*, 9:956-66). These promoters, or other tissue-specific promoters known in the art, are not highly-active in HEK-293 cells and, thus, will not expected to yield significant levels of endonuclease gene expression in packaging cells when incorporated into viral vectors of the present invention. Similarly, the viral vectors of the present invention contemplate the use of other cell lines with the use of incompatible tissue specific promoters (*i.e.*, the well-known HeLa cell line (human epithelial cell) and using the liver-specific hemopexin promoter). Other examples of tissue specific promoters include: synovial sarcomas PDZD4 (cerebellum), C6 (liver), ASB5 (muscle), PPP1R12B (heart), SLC5A12 (kidney), cholesterol regulation APOM (liver), ADPRHL1 (heart), and monogenic malformation syndromes TP73L (muscle). (Jacox E, *et al.*, (2010) *PLoS One*

v.5(8):e12274).

2. Alternatively, the vector can be packaged in cells from a different species in which the endonuclease is not likely to be expressed. For example, viral particles can be produced in microbial, insect, or plant cells using mammalian promoters, such as the well-known cytomegalovirus- or SV40 virus-early promoters, which are not active in the non-mammalian packaging cells. In a preferred embodiment, viral particles are produced in insect cells using the baculovirus system as described by Gao, et al. (Gao, H., *et al.* (2007) *J. Biotechnol.* 131(2):138-43). An endonuclease under the control of a mammalian promoter is unlikely to be expressed in these cells (Airenne, KJ, *et al.* (2013) *Mol. Ther.* 21(4):739-49). Moreover, insect cells utilize different mRNA splicing motifs than mammalian cells. Thus, it is possible to incorporate a mammalian intron, such as the human growth hormone (HGH) intron or the SV40 large T antigen intron, into the coding sequence of an endonuclease. Because these introns are not spliced efficiently from pre-mRNA transcripts in insect cells, insect cells will not express a functional endonuclease and will package the full-length genome. In contrast, mammalian cells to which the resulting recombinant AAV particles are delivered will properly splice the pre-mRNA and will express functional endonuclease protein. Haifeng Chen has reported the use of the HGH and SV40 large T antigen introns to attenuate expression of the toxic proteins barnase and diphtheria toxin fragment A in insect packaging cells, enabling the production of recombinant AAV vectors carrying these toxin genes (Chen, H (2012) *Mol Ther Nucleic Acids*. 1(11): e57).
3. The endonuclease gene can be operably linked to an inducible promoter such that a small-molecule inducer is required for endonuclease expression. Examples of inducible promoters include the Tet-On system (Clontech; Chen H., *et al.*, (2015) *BMC Biotechnol.* 15(1):4)) and the RheoSwitch system (Intrexon; Sowa G., *et al.*, (2011) *Spine*, 36(10): E623-8). Both systems, as well as similar systems known in the art, rely on ligand-inducible transcription factors (variants of the Tet Repressor and Ecdysone receptor, respectively) that activate transcription in response to a small-molecule activator (Doxycycline or Ecdysone, respectively). Practicing the current invention using such ligand-inducible transcription activators includes: 1) placing the endonuclease gene under the control of a promoter that responds to the

corresponding transcription factor, the endonuclease gene having (a) binding site(s) for the transcription factor; and 2) including the gene encoding the transcription factor in the packaged viral genome. The latter step is necessary because the endonuclease will not be expressed in the target cells or tissues following recombinant AAV delivery if the transcription activator is not also provided to the same cells. The transcription activator then induces endonuclease gene expression only in cells or tissues that are treated with the cognate small-molecule activator. This approach is advantageous because it enables endonuclease gene expression to be regulated in a spatio-temporal manner by selecting when and to which tissues the small-molecule inducer is delivered. However, the requirement to include the inducer in the viral genome, which has significantly limited carrying capacity, creates a drawback to this approach.

4. In another preferred embodiment, recombinant AAV particles are produced in a mammalian cell line that expresses a transcription repressor that prevents expression of the endonuclease. Transcription repressors are known in the art and include the Tet-Repressor, the Lac-Repressor, the Cro repressor, and the Lambda-repressor. Many nuclear hormone receptors such as the ecdysone receptor also act as transcription repressors in the absence of their cognate hormone ligand. To practice the current invention, packaging cells are transfected/transduced with a vector encoding a transcription repressor and the endonuclease gene in the viral genome (packaging vector) is operably linked to a promoter that is modified to comprise binding sites for the repressor such that the repressor silences the promoter. The gene encoding the transcription repressor can be placed in a variety of positions. It can be encoded on a separate vector; it can be incorporated into the packaging vector outside of the ITR sequences; it can be incorporated into the cap/rep vector or the adenoviral helper vector; or, most preferably, it can be stably integrated into the genome of the packaging cell such that it is expressed constitutively. Methods to modify common mammalian promoters to incorporate transcription repressor sites are known in the art. For example, Chang and Roninson modified the strong, constitutive CMV and RSV promoters to comprise operators for the Lac repressor and showed that gene expression from the modified promoters was greatly attenuated in cells expressing the repressor (Chang BD, and Roninson IB (1996) *Gene* 183:137-42). The use of a non-human

transcription repressor ensures that transcription of the endonuclease gene will be repressed only in the packaging cells expressing the repressor and not in target cells or tissues transduced with the resulting recombinant AAV vector.

2.6 Engineered Nuclease Variants

[0338] Embodiments of the invention encompass the engineered nucleases described herein, and variants thereof. Further embodiments of the invention encompass isolated polynucleotides comprising a nucleic acid sequence encoding the endonucleases described herein, and variants of such polynucleotides.

[0339] As used herein, “variants” is intended to mean substantially similar sequences. A “variant” polypeptide is intended to mean a polypeptide derived from the “native” polypeptide by deletion or addition of one or more amino acids at one or more internal sites in the native protein and/or substitution of one or more amino acids at one or more sites in the native polypeptide. As used herein, a “native” polynucleotide or polypeptide comprises a parental sequence from which variants are derived. Variant polypeptides encompassed by the embodiments are biologically active. That is, they continue to possess the desired biological activity of the native protein; i.e., the ability to recognize and cleave recognition sequences found in an int22h-1 sequence in a Factor VIII gene including, for example, the F8R 1-2 recognition sequence (SEQ ID NO: 7), the F8R 3-4 recognition sequence (SEQ ID NO: 9), the F8R 9-10 recognition sequence (SEQ ID NO: 11), the F8R 11-12 recognition sequence (SEQ ID NO: 13), the F8R 13-14 recognition sequence (SEQ ID NO: 15), or the F8R 15-16 recognition sequence (SEQ ID NO: 17). Such variants may result, for example, from human manipulation. Biologically active variants of a native polypeptide of the embodiments (e.g., SEQ ID NOs: 19-21, 28-31, 40-43, 52-55, 64-67, or 76-79), or biologically active variants of the recognition half-site binding subunits described herein, will have at least about 40%, about 45%, about 50%, about 55%, about 60%, about 65%, about 70%, about 75%, about 80%, about 85%, about 90%, about 91%, about 92%, about 93%, about 94%, about 95%, about 96%, about 97%, about 98%, or about 99%, sequence identity to the amino acid sequence of the native polypeptide or native subunit, as determined by sequence alignment programs and parameters described elsewhere herein. A biologically active variant of a polypeptide or subunit of the embodiments may differ from that polypeptide or subunit by as

few as about 1-40 amino acid residues, as few as about 1-20, as few as about 1-10, as few as about 5, as few as 4, 3, 2, or even 1 amino acid residue.

[0340] The polypeptides of the embodiments may be altered in various ways including amino acid substitutions, deletions, truncations, and insertions. Methods for such manipulations are generally known in the art. For example, amino acid sequence variants can be prepared by mutations in the DNA. Methods for mutagenesis and polynucleotide alterations are well known in the art. See, for example, Kunkel (1985) *Proc. Natl. Acad. Sci. USA* 82:488-492; Kunkel et al. (1987) *Methods in Enzymol.* 154:367-382; U.S. Pat. No. 4,873,192; Walker and Gaastra, eds. (1983) *Techniques in Molecular Biology* (MacMillan Publishing Company, New York) and the references cited therein. Guidance as to appropriate amino acid substitutions that do not affect biological activity of the protein of interest may be found in the model of Dayhoff et al. (1978) *Atlas of Protein Sequence and Structure* (Natl. Biomed. Res. Found., Washington, D.C.), herein incorporated by reference. Conservative substitutions, such as exchanging one amino acid with another having similar properties, may be optimal.

[0341] A substantial number of amino acid modifications to the DNA recognition domain of the wild-type I-CreI meganuclease have previously been identified (e.g., U.S. 8,021,867) which, singly or in combination, result in recombinant meganucleases with specificities altered at individual bases within the DNA recognition sequence half-site, such that the resulting rationally-designed meganucleases have half-site specificities different from the wild-type enzyme. Table 7 provides potential substitutions that can be made in a recombinant meganuclease monomer or subunit to enhance specificity based on the base present at each half-site position (-1 through -9) of a recognition half-site.

Table 7.

	Favored Sense-Strand Base										
Posn.	A	C	G	T	A/T	A/C	A/G	C/T	G/T	A/G/T	A/C/G/T
-1	Y75 L75* C75* Y139* C46* A46*	R70* H75* R75* H46* K46* R46*	K70 E70* E75* E46* D46*	Q70* C70 L70 Y75* Q75* H75* H139 Q46* H46*				T46*			G70 A70 S70 G46*
-2	Q70 T44* A44* V44* I44* L44* N44*	E70 D70 K44* R44*	H70 D44* E44*	Q44*	C44*						
-3	Q68 C24* I24*	E68 F68 K24* R24*	R68	M68 C68 L68 F68		H68		Y68	K68		
-4	A26* Q77	E77 K26*	R77 E26*					S77 Q26*			S26*
-5		E42	R42			K28*	C28* Q42				M66 K66
-6	Q40 C28*	E40 R28*	R40	C40 I40 V40 C79 I79 V79 Q28*	A40 A79 A28* H28*						S40 S28*
-7	N30* Q38	E38 K30* R30*	K38 R38 E30*	I38 L38			C38				H38 N38 Q30*
-8	F33 Y33	E33 D33	F33 H33	L33 V33 I33 F33 C33		R32*	R33				

	Favored Sense-Strand Base									
-9		E32	R32 K32	L32 V32 A32 C32				D32 I32		S32 N32 H32 Q32 T32

Bold entries are wild-type contact residues and do not constitute “modifications” as used herein. An asterisk indicates that the residue contacts the base on the antisense strand.

[0342] For polynucleotides, a “variant” comprises a deletion and/or addition of one or more nucleotides at one or more sites within the native polynucleotide. One of skill in the art will recognize that variants of the nucleic acids of the embodiments will be constructed such that the open reading frame is maintained. For polynucleotides, conservative variants include those sequences that, because of the degeneracy of the genetic code, encode the amino acid sequence of one of the polypeptides of the embodiments. Variant polynucleotides include synthetically derived polynucleotides, such as those generated, for example, by using site-directed mutagenesis but which still encode a recombinant meganuclease of the embodiments. Generally, variants of a particular polynucleotide of the embodiments will have at least about 40%, about 45%, about 50%, about 55%, about 60%, about 65%, about 70%, about 75%, about 80%, about 85%, about 90%, about 91%, about 92%, about 93%, about 94%, about 95%, about 96%, about 97%, about 98%, about 99% or more sequence identity to that particular polynucleotide as determined by sequence alignment programs and parameters described elsewhere herein. Variants of a particular polynucleotide of the embodiments (i.e., the reference polynucleotide) can also be evaluated by comparison of the percent sequence identity between the polypeptide encoded by a variant polynucleotide and the polypeptide encoded by the reference polynucleotide.

[0343] The deletions, insertions, and substitutions of the protein sequences encompassed herein are not expected to produce radical changes in the characteristics of the polypeptide. However, when it is difficult to predict the exact effect of the substitution, deletion, or insertion in advance of doing so, one skilled in the art will appreciate that the effect will be evaluated by screening the polypeptide for its ability to preferentially recognize and cleave recognition sequences found within an int22h-1 sequence of a Factor VIII gene.

EXAMPLES

[0344] This invention is further illustrated by the following examples, which should not be construed as limiting. Those skilled in the art will recognize, or be able to ascertain, using no more than routine experimentation, numerous equivalents to the specific substances and procedures described herein. Such equivalents are intended to be encompassed in the scope of the claims that follow the examples below.

EXAMPLE 1

Characterization of Meganucleases That Recognize and Cleave F8R Recognition Sequences

1. Meganucleases that recognize and cleave the F8R 1-2 recognition sequence

[0345] Recombinant meganucleases (SEQ ID NOs: 19-21), collectively referred to herein as “F8R 1-2 meganucleases,” were engineered to recognize and cleave the F8R 1-2 recognition sequence (SEQ ID NO: 7), which is present in the human and canine Factor VIII gene, specifically within the int22h-1 sequence, and more specifically within the F8A1 sequence. Each F8R 1-2 recombinant meganuclease comprises an N-terminal nuclease-localization signal derived from SV40, a first meganuclease subunit, a linker sequence, and a second meganuclease subunit. A first subunit in each F8R 1-2 meganuclease binds to the F8R1 recognition half-site of SEQ ID NO: 7, while a second subunit binds to the F8R2 recognition half-site (see, Fig. 2).

[0346] The F8R1-binding subunits and F8R2-binding subunits each comprise a 56 base pair hypervariable region, referred to as HVR1 and HVR2, respectively. F8R1-binding subunits are highly conserved outside of the HVR1 region. Similarly, F8R2-binding subunits are also highly conserved outside of the HVR2 region. The F8R1-binding regions of SEQ ID NOs: 19-21 are provided as SEQ ID NOs: 22-24, respectively. Each of SEQ ID NOs: 22-24 share at least 90% sequence identity to SEQ ID NO: 22, which is the F8R1-binding region of the meganuclease F8R 1-2x.27 (SEQ ID NO: 19). F8R2-binding regions of SEQ ID NOs: 19-21 are provided as SEQ ID NOs: 25-27, respectively. Each of SEQ ID NOs: 25-27 share at least 90% sequence identity to SEQ ID NO: 25, which is the F8R2-binding region of the meganuclease F8R 1-2x.27 (SEQ ID NO: 19).

2. Meganucleases that recognize and cleave the F8R 3-4 recognition sequence

[0347] Recombinant meganucleases (SEQ ID NOs: 28-31), collectively referred to herein as “F8R 3-4 meganucleases,” were engineered to recognize and cleave the F8R 3-4 recognition sequence (SEQ ID NO: 9), which is present in the human and canine Factor VIII gene, specifically within the int22h-1 sequence, and more specifically within the F8A1 sequence. Each F8R 3-4 recombinant meganuclease comprises an N-terminal nuclease-localization signal derived from SV40, a first meganuclease subunit, a linker sequence, and a second meganuclease subunit. A first subunit in each F8R 3-4 meganuclease binds to the F8R3 recognition half-site of SEQ ID NO: 9, while a second subunit binds to the F8R4 recognition half-site (see, Fig. 2).

[0348] The F8R3-binding subunits and F8R4-binding subunits each comprise a 56 base pair hypervariable region, referred to as HVR1 and HVR2, respectively. F8R3-binding subunits are highly conserved outside of the HVR1 region. Similarly, F8R4-binding subunits are also highly conserved outside of the HVR2 region. The F8R3-binding regions of SEQ ID NOs: 28-31 are provided as SEQ ID NOs: 32-35, respectively. Each of SEQ ID NOs: 32-35 share at least 90% sequence identity to SEQ ID NO: 32, which is the F8R3-binding region of the meganuclease F8R 3-4x.43 (SEQ ID NO: 28). F8R4-binding regions of SEQ ID NOs: 28-31 are provided as SEQ ID NOs: 36-39, respectively. Each of SEQ ID NOs: 36-39 share at least 90% sequence identity to SEQ ID NO: 36, which is the F8R4-binding region of the meganuclease F8R 3-4x.43 (SEQ ID NO: 28).

3. Meganucleases that recognize and cleave the F8R 9-10 recognition sequence

[0349] Recombinant meganucleases (SEQ ID NOs: 40-43), collectively referred to herein as “F8R 9-10 meganucleases,” were engineered to recognize and cleave the F8R 9-10 recognition sequence (SEQ ID NO: 11), which is present in the human and canine Factor VIII gene, specifically within the int22h-1 sequence. Each F8R 9-10 recombinant meganuclease comprises an N-terminal nuclease-localization signal derived from SV40, a first meganuclease subunit, a linker sequence, and a second meganuclease subunit. A first subunit in each F8R 9-10 meganuclease binds to the F8R9 recognition half-site of SEQ ID NO: 11, while a second subunit binds to the F8R10 recognition half-site (see, Fig. 2).

[0350] The F8R9-binding subunits and F8R10-binding subunits each comprise a 56 base pair hypervariable region, referred to as HVR1 and HVR2, respectively. F8R9-binding

subunits are highly conserved outside of the HVR1 region. Similarly, F8R10-binding subunits are also highly conserved outside of the HVR2 region. The F8R9-binding regions of SEQ ID NOs: 40-43 are provided as SEQ ID NOs: 44-47, respectively. Each of SEQ ID NOs: 44-47 share at least 90% sequence identity to SEQ ID NO: 44, which is the F8R9-binding region of the meganuclease F8R 9-10x.70 (SEQ ID NO: 40). F8R10-binding regions of SEQ ID NOs: 40-43 are provided as SEQ ID NOs: 48-51, respectively. Each of SEQ ID NOs: 48-51 share at least 90% sequence identity to SEQ ID NO: 48, which is the F8R10-binding region of the meganuclease F8R 9-10x.70 (SEQ ID NO: 40).

4. Meganucleases that recognize and cleave the F8R 11-12 recognition sequence

[0351] Recombinant meganucleases (SEQ ID NOs: 52-55), collectively referred to herein as “F8R 11-12 meganucleases,” were engineered to recognize and cleave the F8R 11-12 recognition sequence (SEQ ID NO: 13), which is present in the human and canine Factor VIII gene, specifically within the int22h-1 sequence. Each F8R 11-12 recombinant meganuclease comprises an N-terminal nuclease-localization signal derived from SV40, a first meganuclease subunit, a linker sequence, and a second meganuclease subunit. A first subunit in each F8R 11-12 meganuclease binds to the F8R11 recognition half-site of SEQ ID NO: 13, while a second subunit binds to the F8R12 recognition half-site (see, Fig. 2).

[0352] The F8R11-binding subunits and F8R12-binding subunits each comprise a 56 base pair hypervariable region, referred to as HVR1 and HVR2, respectively. F8R11-binding subunits are highly conserved outside of the HVR1 region. Similarly, F8R12-binding subunits are also highly conserved outside of the HVR2 region. The F8R11-binding regions of SEQ ID NOs: 52-55 are provided as SEQ ID NOs: 56-59, respectively. Each of SEQ ID NOs: 56-59 share at least 90% sequence identity to SEQ ID NO: 56, which is the F8R11-binding region of the meganuclease F8R 11-12x.56 (SEQ ID NO: 52). F8R12-binding regions of SEQ ID NOs: 52-55 are provided as SEQ ID NOs: 60-63, respectively. Each of SEQ ID NOs: 60-63 share at least 90% sequence identity to SEQ ID NO: 60, which is the F8R12-binding region of the meganuclease F8R 11-12x.56 (SEQ ID NO: 52).

5. Meganucleases that recognize and cleave the F8R 13-14 recognition sequence

[0353] Recombinant meganucleases (SEQ ID NOs: 64-67), collectively referred to herein as “F8R 13-14 meganucleases,” were engineered to recognize and cleave the F8R 13-14

recognition sequence (SEQ ID NO: 15), which is present in the human and canine Factor VIII gene, specifically within the int22h-1 sequence. Each F8R 13-14 recombinant meganuclease comprises an N-terminal nuclease-localization signal derived from SV40, a first meganuclease subunit, a linker sequence, and a second meganuclease subunit. A first subunit in each F8R 13-14 meganuclease binds to the F8R13 recognition half-site of SEQ ID NO: 15, while a second subunit binds to the F8R14 recognition half-site (see, Fig. 2).

[0354] The F8R13-binding subunits and F8R14-binding subunits each comprise a 56 base pair hypervariable region, referred to as HVR1 and HVR2, respectively. F8R13-binding subunits are highly conserved outside of the HVR1 region. Similarly, F8R14-binding subunits are also highly conserved outside of the HVR2 region. The F8R13-binding regions of SEQ ID NOs: 64-67 are provided as SEQ ID NOs: 68-71, respectively. Each of SEQ ID NOs: 68-71 share at least 90% sequence identity to SEQ ID NO: 68, which is the F8R13-binding region of the meganuclease F8R 13-14x.13 (SEQ ID NO: 64). F8R14-binding regions of SEQ ID NOs: 64-67 are provided as SEQ ID NOs: 72-75, respectively. Each of SEQ ID NOs: 72-75 share at least 90% sequence identity to SEQ ID NO: 72, which is the F8R14-binding region of the meganuclease F8R 13-14x.13 (SEQ ID NO: 64).

6. Meganucleases that recognize and cleave the F8R 15-16 recognition sequence

[0355] Recombinant meganucleases (SEQ ID NOs: 76-79), collectively referred to herein as “F8R 15-16 meganucleases,” were engineered to recognize and cleave the F8R 15-16 recognition sequence (SEQ ID NO: 17), which is present in the human and canine Factor VIII gene, specifically within the int22h-1 sequence. Each F8R 15-16 recombinant meganuclease comprises an N-terminal nuclease-localization signal derived from SV40, a first meganuclease subunit, a linker sequence, and a second meganuclease subunit. A first subunit in each F8R 15-16 meganuclease binds to the F8R15 recognition half-site of SEQ ID NO: 17, while a second subunit binds to the F8R16 recognition half-site (see, Fig. 2).

[0356] The F8R15-binding subunits and F8R16-binding subunits each comprise a 56 base pair hypervariable region, referred to as HVR1 and HVR2, respectively. F8R15-binding subunits are highly conserved outside of the HVR1 region. Similarly, F8R16-binding subunits are also highly conserved outside of the HVR2 region. The F8R15-binding regions of SEQ ID NOs: 76-79 are provided as SEQ ID NOs: 80-83, respectively. Each of SEQ ID NOs: 80-83 share at least 90% sequence identity to SEQ ID NO: 80, which is the F8R15-

binding region of the meganuclease F8R 15-16x.14 (SEQ ID NO: 76). F8R16-binding regions of SEQ ID NOs: 76-79 are provided as SEQ ID NOs: 84-87, respectively. Each of SEQ ID NOs: 84-87 share at least 90% sequence identity to SEQ ID NO: 84, which is the F8R16-binding region of the meganuclease F8R 15-16x.14 (SEQ ID NO: 76).

7. Cleavage of F8R recognition sequences in a CHO cell reporter assay

[0357] To determine whether F8R 1-2, F8R 3-4, F8R 9-10, F8R 11-12, F8R 13-14, and F8R 15-16 meganucleases could recognize and cleave their respective recognition sequences (SEQ ID NOs: 7, 9, 11, 13, 15, and 17, respectively), each recombinant meganuclease was evaluated using the CHO cell reporter assay previously described (see, WO/2012/167192 and Fig. 4). To perform the assays, CHO cell reporter lines were produced which carried a non-functional Green Fluorescent Protein (GFP) gene expression cassette integrated into the genome of the cells. The GFP gene in each cell line was interrupted by a pair of recognition sequences such that intracellular cleavage of either recognition sequence by a meganuclease would stimulate a homologous recombination event resulting in a functional GFP gene.

[0358] In CHO reporter cell lines developed for this study, one recognition sequence inserted into the GFP gene was the F8R 1-2 recognition sequence (SEQ ID NO: 7), the F8R 3-4 recognition sequence (SEQ ID NO: 9), the F8R 9-10 recognition sequence (SEQ ID NO: 11), the F8R 11-12 recognition sequence (SEQ ID NO: 13), the F8R 13-14 recognition sequence (SEQ ID NO: 15), or the F8R 15-16 recognition sequence (SEQ ID NO: 17). The second recognition sequence inserted into the GFP gene was a CHO-23/24 recognition sequence, which is recognized and cleaved by a control meganuclease called “CHO-23/24”. CHO reporter cells comprising the F8R 1-2 recognition sequence and the CHO-23/24 recognition sequence are referred to as “F8R 1-2 cells.” CHO reporter cells comprising the F8R 3-4 recognition sequence and the CHO-23/24 recognition sequence are referred to as “F8R 3-4 cells.” CHO reporter cells comprising the F8R 9-10 recognition sequence and the CHO-23/24 recognition sequence are referred to as “F8R 9-10 cells.” CHO reporter cells comprising the F8R 11-12 recognition sequence and the CHO-23/24 recognition sequence are referred to as “F8R 11-12 cells.” CHO reporter cells comprising the F8R 13-14 recognition sequence and the CHO-23/24 recognition sequence are referred to as “F8R 13-14 cells.” CHO reporter cells comprising the F8R 15-16 recognition sequence and the CHO-23/24 recognition sequence are referred to as “F8R 15-16 cells.”

[0359] CHO reporter cells were transfected with plasmid DNA encoding their corresponding recombinant meganucleases (e.g., F8R 1-2 cells were transfected with plasmid DNA encoding F8R 1-2 meganucleases) or encoding the CHO-23/34 meganuclease. In each assay, 4e5 CHO reporter cells were transfected with 50 ng of plasmid DNA in a 96-well plate using Lipofectamine® 2000 (ThermoFisher) according to the manufacturer's instructions. At 48 hours post-transfection, cells were evaluated by flow cytometry to determine the percentage of GFP-positive cells compared to an untransfected negative control (F8R bs). As shown in Figs. 5A-5G, all F8R meganucleases were found to produce GFP-positive cells in cell lines comprising their corresponding recognition sequence at frequencies significantly exceeding the negative control.

[0360] The efficacy of PCS 7-8 meganucleases was also determined in a time-dependent manner 2, 5, 7, 9, and 12 days, after introduction of the meganucleases into CHO reporter cells. In this study, F8R 1-2, F8R 3-4, F8R 9-10, F8R 11-12, F8R 13-14, or F8R 15-16 cells (1.0×10^6) were electroporated with 1×10^6 copies of their corresponding meganuclease mRNA per cell using a BioRad Gene Pulser Xcell™ according to the manufacturer's instructions. At the designated time points post-transfection, cells were evaluated by flow cytometry to determine the percentage of GFP-positive cells. A CHO-23/24 meganuclease was also included at each time point as a positive control.

[0361] As shown in Figs. 6A-6F, the %GFP produced by a number of different F8R meganucleases was relatively consistent over the time course of each study, indicating persistent cleavage activity and a lack of any substantial toxicity in the cells. Other F8R meganucleases exhibited some variability in %GFP expression over the time course of the study.

8. Conclusions

[0362] These studies demonstrated that F8R meganucleases encompassed by the invention can efficiently target and cleave their respective recognition sequences in cells.

EXAMPLE 2Inversion of Exons 1-22 in the Human Factor VIII Gene1. Production of indels at recognition sequences in mammalian cells

[0363] Meganucleases F8R 1-2 and F8R 3-4 were tested for the ability to cut and cause insertions and/or deletions (indels) at their recognition sites by T7 endonuclease assay. HEK 293 cells were transfected with 200ng of mRNA encoding each nuclease. Cells were harvested at 7 days post transfection and gDNA was extracted. This gDNA was used as a template in PCR reactions using primers F8R3-4f.357 and F8R1-2r.467. The resulting PCR product was then analyzed using T7 endonuclease to reveal the presence of indels (Fig. 7). Fig. 7 illustrates an agarose gel loaded with PCR/T7 endonuclease reactions from HEK 293 cells that were mock treated (Lane 1) or treated with F8R 1-2x.15 (lane 2), F8R 1-2x.27 (lane 3), F8R 3-4x.43 (lane 4), or F8R 3-4x.70 (lane 5). The lower molecular weight bands in lanes 4 and 5 are indicative of a positive T7 endonuclease result and the presence of indels at the targeted recognition sequences.

2. Inversion of exons 1-22 in mammalian cells

[0364] To determine if cleavage of genomic DNA by F8R 1-2 and F8R 3-4 meganucleases could stimulate an inversion of exons 1-22, we first transfected HEK 293 cells with 200ng of mRNA encoding either F8R 1-2 or F8R 3-4 meganucleases and harvested gDNA 7 days later. The gDNA was analyzed by PCR using primer set H1R/H1F to detect normal exon 1-22 positioning and with primer set H1R/H2/3R to detect inverted exon 1-22 positioning (Fig. 8). Fig. 8A illustrates an agarose gel loaded with H1R/H1F primed PCR reactions from HEK 293 cells that were mock treated (lane 1), or treated with F8R 1-2x.15 (lane 2), F8R 1-2x.27 (lane 3), F8R 3-4x.43 (lane 4), F8R 3-4x.70 (lane 5). Lane 6 contains a control PCR using untreated human cell gDNA template. Lane 7 contains a no template PCR negative control. Fig. 8B illustrates an agarose gel loaded with H1R/H2/3R primed PCR reactions from HEK 293 cells that were mock treated (lane 1), or treated with F8R 1-2x.15 (lane 2), F8R 1-2x.27 (lane 3), F8R 3-4x.43 (lane 4), F8R 3-4x.70 (lane 5). Lane 6 contains a control PCR using untreated human cell gDNA template. Lane 7 contains a no template PCR

negative control. The presence of PCR fragments in Fig. 8B is indicative of successful exon 1-22 inversion using F8R meganucleases encompassed by the invention.

[0365] To determine if cleavage of genomic DNA by F8R 9-10, F8R 11-12, F8R 13-14, and F8R 15-16 meganucleases could stimulate an inversion of exons 1-22, we first transfected HEK 293 cells with 200ng of mRNA encoding each individual nuclease and harvested gDNA at day 2 and day 8 post transfection. The gDNA was analyzed by PCR using primer set H1R/H1F, which detects normal exon 1-22 positioning, and with primer set H1R/H2/3R, which detects inverted exon 1-22 positioning (Fig. 9). Fig. 9 illustrates an agarose gel loaded with H1R/H1F primed PCR reactions (top) and H1R/H2/3R primed PCR reactions (bottom) from HEK 293 cells that were mock treated (lane 1), or treated with F8R 9-10x.38 (lane 2), F8R 9-10x.70 (lane 3), F8R 11-12x.56 (lane 4), F8R 11-12x.69 (lane 5), F8R 13-14x.3 (lane 6), F8R 13-14x.13 (lane 7), F8R 15-16x.14 (lane 8), or F8R 15-16x.85 (lane 9). Lane 10 contains a control PCR using untreated human cell gDNA template. Lane 11 contains a no template PCR negative control. The presence of PCR fragments in H1R/H2/3R primed PCR reactions (lower half of Fig. 9) is indicative of successful exon 1-22 inversion using the F8R meganucleases encompassed by the invention.

EXAMPLE 3

Inversion of Factor VIII gene by F8R nucleases in 293 cells and determination of efficiency by inverse digital PCR

1. Materials and Methods

[0366] This study demonstrated that F8R nucleases encompassed by this invention can lead to the hemophilia A specific Factor VIII gene inversion in HEK293cells. In addition, the described method can be used to determine the efficiency of F8R nuclease-mediated Factor VIII gene inversion.

[0367] HEK293 cells (2×10^6) were transfected with mRNA (5 μ g) encoding F8R11-12x.69 or F8R13-14x.13 nucleases, respectively, using a Bio-Rad GenePulser XCell according to the manufacturer's instructions. At 2 days post-transfection, genomic DNA was isolated from cells and inverse digital PCR was performed to determine Factor VIII genome editing. Genomic DNA isolated from untransfected cells served as a control.

[0368] Genomic DNA was digested to completion with restriction endonuclease BclI. Digested DNA was circularized using T4 DNA ligase and analyzed by inverse digital PCR using the Bio-Rad QX200 Digital PCR System according to the manufacturer's instructions. In normal human genomic DNA, the BclI digest generates an approximately 21 kb fragment encompassing the int22h-1 repeat in intron 22 of the Factor VIII gene as well as an approximately 16 kb fragment encompassing a near-identical, inversely oriented copy of the int22h-1 repeat located about 0.5 Mb upstream of int22h-1.

[0369] In inverse digital PCR, the two circularized BclI fragments described above are amplified with primers flanking the respective BclI sites. Primers U1 and D1 bind upstream and downstream, respectively of the int22h-1 repeat in intron 22 of the Factor VIII gene; primer U3 binds upstream of a near-identical, inversely oriented copy of the int22h-1 repeat located about 0.5 Mb upstream of int22h-1. All primers bind the genomic DNA in opposite orientation to conventional PCR and generate amplicons only when the BclI fragments are circularized.

U1: [5'-CCTTTCAACTCCATCTCCAT-3'] (SEQ ID NO: 88)

D1: [5'-ACATACGGTTTAGTCACAAGT-3'] (SEQ ID NO: 89)

U3: [5'-TCCAGTCACTTAGGCTCAG-3'] (SEQ ID NO: 90)

[0370] Inverse digital PCR of HEK293 genomic DNA with primers U1/D1 yields an approximately 0.5 kb amplicon that can be detected using a TaqMan probe while PCR with primers U3/U1 does not generate an amplification product.

[0371] Upon successful inversion of the genomic fragment between int22h-1 and its distal copy, the U1 primer binding site, which is located on the inverted fragment, is reoriented relative to the D1 and U3 primer binding sites. Now, the U1/D1 PCR fails to generate a PCR product, while the U3/U1 PCR yields an approximately 0.5 kb amplicon which can be detected with the same TaqMan probe.

2. Results

[0372] Genomic DNAs from HEK293 cells and HEK293 cells treated with F8R11-12x.69 or F8R13-14x.13 nucleases, respectively, were analyzed by inverse digital PCR. Only the U1/D1 fragment was amplified from genomic DNA isolated from untreated HEK293 cells, while the U3/U1 PCR did not generate a signal (Fig. 10, mock). Using genomic DNA from F8R nuclease-treated HEK293 cells, both U1/D1 and U3/U1 amplicons were detected

(Fig. 10, F8R11-12x.69 and F8R13-14x.13). The U1/D1 fragment was still amplified from genomic DNA from F8R nuclease-treated HEK293 cells because the nuclease treatment generated a mixed population of cells with both edited and unedited genomes. Since digital PCR allows parallel analysis of hundreds to thousands of chromosome equivalents, the Factor VIII gene inversion efficiency could be calculated. Out of the total number of Factor VIII genes detected by this assay, 4% and 30% showed an inversion as a result of the activity of nucleases F8R13-14x.13 and F8R11-12x.69, respectively.

3. Conclusions

[0373] Inverse digital PCR detected Factor VIII gene inversion in HEK293 cells treated with nucleases F8R11-12x.69 and F8R13-14x.13. In addition, using inverse digital PCR, the editing efficiency could be calculated. Depending on the nuclease (F8R11-12x.69), up to 30% of the detected Factor VIII genes in HEK293 cells were edited. Importantly, this study demonstrates that Factor VIII gene inversions can be induced by DNA double-strand breaks within the int22h repeats. Both nucleases target recognition sequences within the int22h repeats and potentially introduce up to three double-strand breaks per chromosome.

EXAMPLE 4

Inversion of Factor VIII gene by F8R nucleases in primary human T cells and determination of editing by long-distance PCR

1. Materials and Methods

[0374] This study demonstrated that F8R nucleases encompassed by this invention can lead to the hemophilia A specific Factor VIII gene inversion in normal wild-type human T-cells. Normal human T-cells (1×10^6) were transfected with mRNA (1 μ g) encoding F8R3-4x.43 nuclease using a Lonza 4D nucleofector according to the manufacturer's instructions. At 3 days post-transfection, genomic DNA was isolated from cells and long-distance PCR was performed to determine Factor VIII genome editing. Genomic DNA isolated from untransfected normal human T-cells served as a control.

[0375] In this long-distance PCR, the genomic DNA was amplified between primers FWD1/REV1 and FWD3/FWD1, respectively.

FWD1: [5'-CCCTTACAGTTATTAAGTACTCTCATGAGGTTTCATTCC-3'] (SEQ ID NO: 91)

REV1: [5'-CCCCGGCACTTGAAAGTAGCAGATGCAAGAAGGGCACA-3'] (SEQ ID NO: 92)

FWD3: [5'-ACTATAACCAGCACCTTGAAGTCCCCTCTCATA-3'] (SEQ ID NO: 93)

[0376] Primers FWD1 and REV1 bind upstream and downstream, respectively of the int22h-1 repeat in intron 22 of the Factor VIII gene; primer FWD3 binds upstream of a near-identical, inversely oriented copy of the int22h-1 repeat located about 0.5 Mb upstream of int22h-1.

[0377] Long-distance PCR of normal human genomic DNA with primers FWD1/REV1 yields an approximately 10 kb amplicon while PCR with primers FWD3/FWD1 does not generate an amplification product.

[0378] Upon successful inversion of the genomic fragment between int22h-1 and its distal copy, the FWD1 primer binding site, which is located on the inverted fragment, is reoriented relative to the REV1 and FWD3 primer binding sites. Now, the FWD1/REV1 PCR fails to generate a PCR product while the FWD3/FWD1 PCR yields an approximately 9.7 kb amplicon. PCR fragments are analyzed by agarose gel electrophoresis and visualized by ethidium bromide.

2. Results

[0379] Genomic DNAs from normal human T-cells and normal human T-cells treated with F8R3-4x.43 nuclease were analyzed by long-distance PCR (Fig. 11). Only the FWD1/REV1 fragment was amplified from genomic DNA isolated from untreated normal human T-cells (lanes 2 and 5). Using genomic DNA from F8R3-4x.43 nuclease-treated normal human T-cells as PCR template, both FWD1/REV1 and FWD3/FWD1 primer combinations yield their signature ~10 kb and ~9.7 kb amplicons, respectively (lanes 3 and 6). The FWD1/REV1 fragment can still be amplified from genomic DNA from F8R3-4x.43 treated normal human T-cells because the nuclease treatment generated a mixed population of cells with edited and unedited genomes.

3. Conclusions

[0380] The F8R3-4x.43 meganuclease was able to generate an inversion of the Factor VIII gene in human T cells by producing a double strand break within the int22h regions, and this inversion could be detected by long-distance PCR.

EXAMPLE 5

Reversion of Factor VIII gene by F8R nucleases in primary human patient T cells and determination of editing by long-distance PCR

1. Materials and Methods

[0381] This study demonstrated that F8R nucleases encompassed by this invention can lead to the reversion of the hemophilia A specific Factor VIII gene inversion in hemophilia A patient T-cells.

[0382] Hemophilia A patient T-cells (1×10^6) were transfected with mRNA (1 μ g) encoding F8R3-4x.43, F8R11-12x.69, or F8R15-16x.14 nucleases, respectively, using a Lonza 4D nucleofector according to the manufacturer's instructions. At 3 days post-transfection, genomic DNA was isolated from cells and long-distance PCR was performed to determine Factor VIII genome editing. Genomic DNA isolated from patient T-cells transfected with mRNA encoding green fluorescent protein (GFP) served as a control.

[0383] In this long-distance PCR, the genomic DNA was amplified between primers H1U/H1D and H3D/H1D, respectively.

H1U: [5'-GCCCTGCCTGTCCATTACACTGATGACATTATGCTGAC-3'] (SEQ ID NO: 94)

H1D: [5'-GGCCCTACAACCATTTCTGCCTTTCACTTTTCAGTGCAATA-3'] (SEQ ID NO: 95)

H3D: [5'-CACAAGGGGGAAGAGTGTGAGGGTGTGGGATAAGAA-3'] (SEQ ID NO: 96)

[0384] Primers H1U and H1D bind upstream and downstream, respectively of the int22h-1 repeat in intron 22 of the Factor VIII gene; primer H3D binds downstream of a near-identical, inversely oriented copy of the int22h-1 repeat located about 0.5 Mb upstream of int22h-1.

[0385] Long-distance PCR of normal human genomic DNA with primers H1U/H1D yields an approximately 12 kb amplicon while PCR with primers H3D/H1D does not generate an amplification product. Conversely, long-distance PCR of genomic DNA from patient cells with the hemophilia A gene inversion with primers H1U/H1D fails to generate a PCR product while the H3D/H1D PCR yields an approximately 11 kb amplicon.

[0386] Upon successful reversion of the genomic fragment in patient T-cells between two inversely oriented int22h repeats, the H1U primer binding site, which is located on the inverted fragment, is reoriented relative to the H3U and H1D primer binding sites. Now the H1U/H1D PCR yields the 12 kb amplicon, indicating a reversion to the wild-type configuration of the Factor VIII gene. PCR fragments were analyzed by agarose gel electrophoresis and visualized by ethidium bromide.

2. Results

[0387] Genomic DNAs from hemophilia A patient T-cells treated with mRNA encoding F8R3-4x.43, F8R11-12x.69, or F8R15-16x.14 nucleases (or GFP as a control) were analyzed by long-distance PCR (Fig. 12). Only the H3U/H1D fragment could be amplified from genomic DNA isolated from patient T-cells treated with GFP mRNA (lanes 1a and 1b). Using genomic DNA from F8R3-4x.43, F8R11-12x.69, or F8R15-16x.14 nuclease-treated patient T-cells as PCR template, both H1U/H1D and H3D/H1D primer combinations yielded their signature wild-type (~12 kb) and inversion (~11 kb) amplicons, respectively (lanes 3a and 3b: F8R3-4x.43; lanes 4a and 4b: F8R11-12x.69; lanes 5a and 5b: F8R15-16x.14). The H3U/H1D fragment was still being amplified from genomic DNA from F8R nuclease-treated patient T-cells because the nuclease treatment generated a mixed population of cells with edited and unedited genomes.

3. Conclusions

[0388] F8R meganucleases encompassed by the invention were capable of inducing a reversion of the inverted Factor VIII gene back to a wild-type configuration in hemophilia A patient T-cells in vitro, and this reversion could be detected by long-distance PCR.

CLAIMS

1. An engineered meganuclease that recognizes and cleaves a recognition sequence within an int22h-1 sequence of a Factor VIII gene, wherein said engineered meganuclease comprises a first subunit and a second subunit, wherein said first subunit binds to a first recognition half-site of said recognition sequence and comprises a first hypervariable (HVR1) region, and wherein said second subunit binds to a second recognition half-site of said recognition sequence and comprises a second hypervariable (HVR2) region.
2. The engineered meganuclease of claim 1, wherein said recognition sequence is within an F8A1 coding sequence of said Factor VIII gene.
3. The engineered meganuclease of claim 2, wherein said F8A1 coding sequence has at least 95% sequence identity to SEQ ID NO: 5 or SEQ ID NO: 6.
4. The engineered meganuclease of any one of claims 1-3, wherein said recognition sequence comprises SEQ ID NO: 9.
5. The engineered meganuclease of claim 4, wherein said HVR1 region comprises an amino acid sequence having at least 80% sequence identity to an amino acid sequence corresponding to residues 215-270 of any one of SEQ ID NOs: 28-31.
6. The engineered meganuclease of claim 4 or claim 5, wherein said HVR1 region comprises residues corresponding to residues 215, 217, 219, 221, 223, 224, 231, 233, 235, 237, 261, 266, and 268 of any one of SEQ ID NOs: 28-31.
7. The engineered meganuclease of any one of claims 4-6, wherein said HVR1 region comprises residues 215-270 of any one of SEQ ID NOs: 28-31.
8. The engineered meganuclease of any one of claims 4-7, wherein said HVR2 region comprises an amino acid sequence having at least 80% sequence identity to an amino acid sequence corresponding to residues 24-79 of any one of SEQ ID NOs: 28-31.

9. The engineered meganuclease of any one of claims 4-8, wherein said HVR2 region comprises residues corresponding to residues 24, 26, 28, 32, 33, 38, 40, 42, 44, 46, 68, 70, 75, and 77 of any one of SEQ ID NOs: 28-31.
10. The engineered meganuclease of any one of claims 4-9, wherein said HVR2 region further comprises a residue corresponding to residue 73 of SEQ ID NO: 30.
11. The engineered meganuclease of any one of claims 4-10, wherein said HVR2 region comprises residues 24-79 of any one of SEQ ID NOs: 28-31.
12. The engineered meganuclease of any one of claims 4-11, wherein said first subunit comprises an amino acid sequence having at least 80% sequence identity to residues 198-344 of any one of SEQ ID NOs: 28-31, and wherein said second subunit comprises an amino acid sequence having at least 80% sequence identity to residues 7-153 of any one of SEQ ID NOs: 28-31.
13. The engineered meganuclease of any one of claims 4-12, wherein said first subunit comprises residues 198-344 of any one of SEQ ID NOs: 28-31.
14. The engineered meganuclease of any one of claims 4-13, wherein said second subunit comprises residues 7-153 of any one of SEQ ID NOs: 28-31.
15. The engineered meganuclease of any one of claims 4-14, wherein said engineered meganuclease is a single-chain meganuclease comprising a linker, wherein said linker covalently joins said first subunit and said second subunit.
16. The engineered meganuclease of any one of claims 4-15, wherein said engineered meganuclease comprises the amino acid sequence of any one of SEQ ID NOs: 28-31.
17. An isolated polynucleotide comprising a nucleic acid sequence encoding said engineered meganuclease of any one of claims 1-16.

18. The isolated polynucleotide of claim 17, wherein said isolated polynucleotide is an mRNA.
19. A recombinant DNA construct comprising a nucleic acid sequence encoding said engineered meganuclease of any one of claims 1-16.
20. The recombinant DNA construct of claim 19, wherein said recombinant DNA construct encodes a viral vector comprising said nucleic acid sequence encoding said engineered meganuclease of any one of claims 1-16.
21. The recombinant DNA construct of claim 19 or claim 20, wherein said viral vector is a recombinant adeno-associated viral (AAV) vector.
22. A viral vector comprising a nucleic acid sequence encoding said engineered meganuclease of any one of claims 1-16.
23. The viral vector of claim 22, wherein said viral vector is a recombinant AAV vector.
24. A pharmaceutical composition for treatment of a subject having hemophilia A characterized by an inversion of exons 1-22 in a Factor VIII gene, said pharmaceutical composition comprising a pharmaceutically acceptable carrier and:
(a) a nucleic acid encoding an engineered nuclease, wherein said engineered nuclease is expressed *in vivo*; or
(b) an engineered nuclease protein;
wherein said engineered nuclease has specificity for a first recognition sequence positioned within an int22h-1 sequence of said Factor VIII gene.
25. The pharmaceutical composition of claim 24, wherein said first recognition sequence is within an F8A1 coding sequence.
26. The pharmaceutical composition of claim 25, wherein said F8A1 coding sequence has at least 95% sequence identity to SEQ ID NO: 5 or SEQ ID NO: 6.

27. The pharmaceutical composition of any one of claims 24-26, wherein said engineered nuclease has specificity for a second recognition sequence that is identical to said first recognition sequence, wherein said second recognition sequence is positioned in a repeat sequence telomeric to said Factor VIII gene in the X chromosome, and wherein said repeat sequence is identical to said int22h-1 sequence except that said repeat sequence is in reverse orientation relative to said int22h-1 sequence.

28. The pharmaceutical composition of any one of claims 24-27, wherein said nucleic acid is an mRNA.

29. The pharmaceutical composition of any one of claims 24-27, wherein said pharmaceutical composition comprises a recombinant DNA construct comprising said nucleic acid.

30. The pharmaceutical composition of any one of claims 24-27, wherein said pharmaceutical composition comprises a viral vector comprising said nucleic acid.

31. The pharmaceutical composition of claim 30, wherein said viral vector is a recombinant AAV vector.

32. The pharmaceutical composition of any one of claims 24-31, wherein said engineered nuclease is an engineered meganuclease, a TALEN, a zinc finger nuclease, a compact TALEN, a CRISPR, or a megaTAL.

33. The pharmaceutical composition of any one of claims 24-32, wherein said engineered nuclease is an engineered meganuclease.

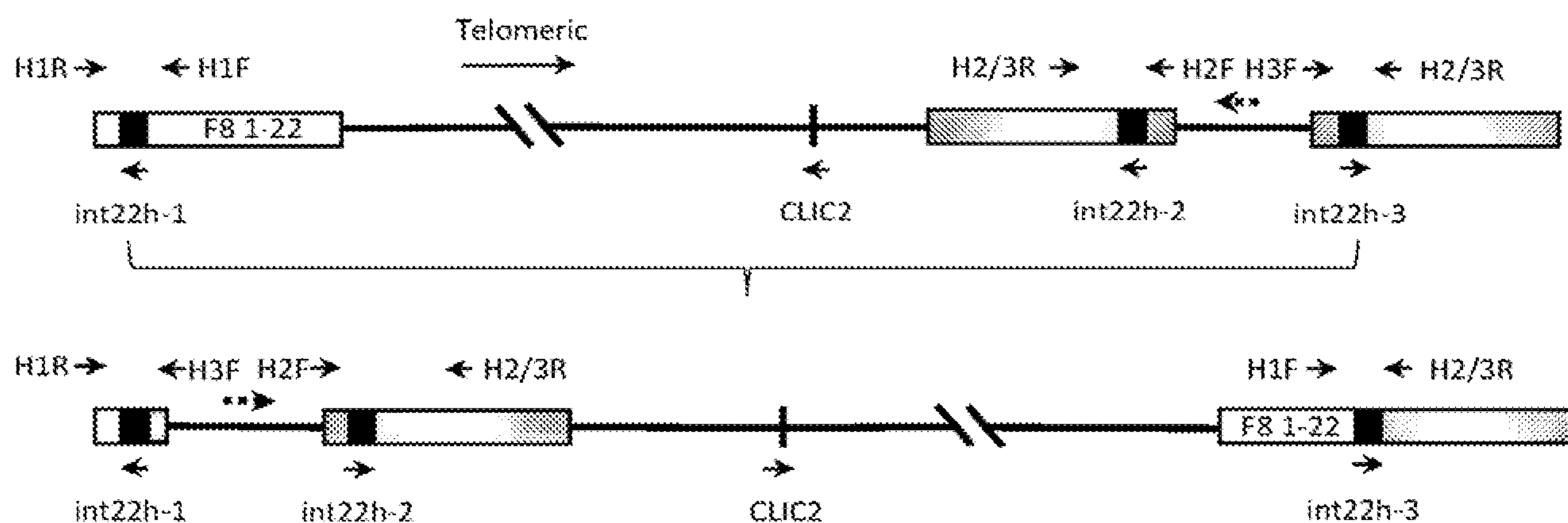
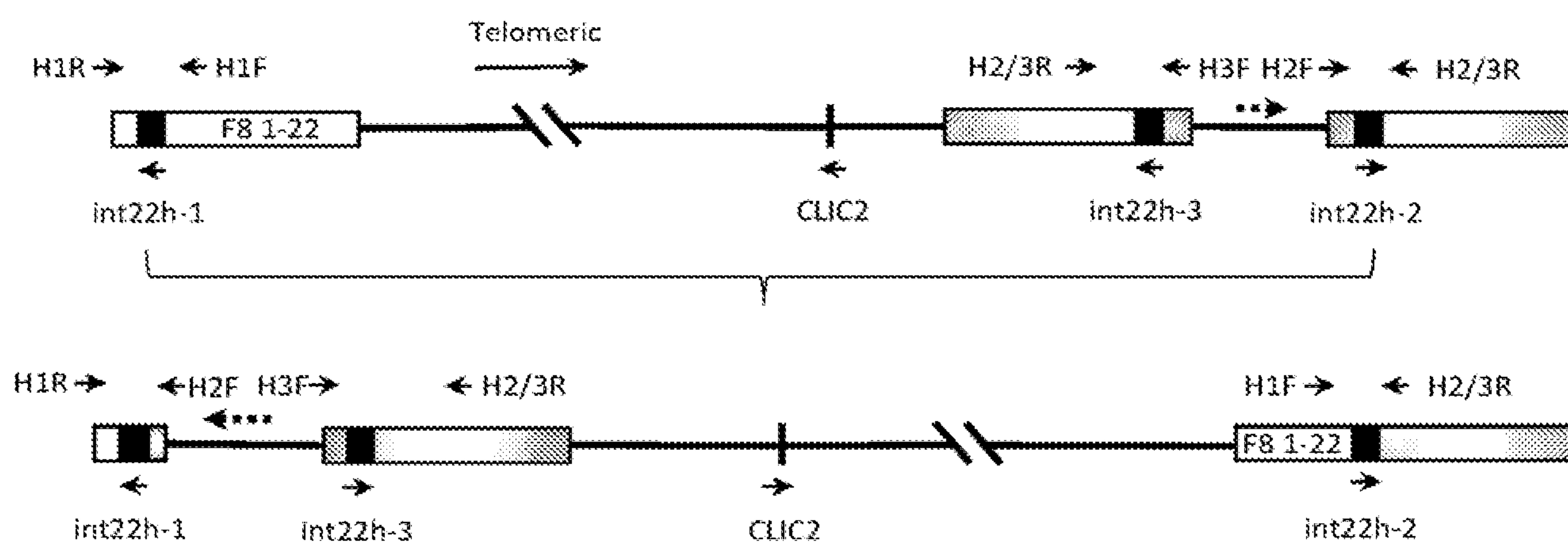
34. The pharmaceutical composition of claim 33, wherein said first recognition sequence comprises SEQ ID NO: 9.

35. The pharmaceutical composition of claim 34, wherein said nucleic acid encodes said engineered meganuclease of any one of claims 4-16.

36. The pharmaceutical composition of claim 35, wherein said engineered meganuclease comprises the amino acid sequence of any one of SEQ ID NOs: 28-31.
37. A method for treating a subject having hemophilia A characterized by an inversion of exons 1-22 of the Factor VIII gene, said method comprising administering to said subject said pharmaceutical composition of any one of claims 24-36.
38. The method of claim 37, wherein said engineered nuclease, or said nucleic acid encoding said engineered nuclease, is delivered to cells which express Factor VIII in a wild-type subject, or progenitor cells which differentiate into cells which express Factor VIII in a wild-type subject.
39. The method of claim 37 or claim 38, wherein said cells are hepatic sinusoidal endothelial cells.
40. The method of claim 37 or claim 38, wherein said cells are progenitor cells which differentiate into hepatic sinusoidal endothelial cells.
41. The method of any one of claims 37-40, wherein said engineered nuclease recognizes and cleaves said first recognition sequence to promote recombination between said int22h-1 sequence and said repeat sequence, resulting in reversion of exons 1-22 to generate a wild-type Factor VIII gene.
42. The method of claim 41, wherein said engineered nuclease further recognizes and cleaves said second recognition sequence in said repeat sequence.
43. The method of any one of claims 37-42, wherein said engineered nuclease is an engineered meganuclease.
44. The method of claim 43, wherein said pharmaceutical composition comprises a nucleic acid encoding said engineered meganuclease of any one of claims 1-16.

45. The method of any one of claims 37-44, wherein said subject is a human.
46. The method of any one of claims 37-44, wherein said subject is a canine.

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Fig. 1A**Fig. 1B**

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	F8R1	F8R2	
	Half-Site	Half-Site	
F8R 1-2	CCAGGCGCTGCATGCGCGTGAA		SEQ ID NO: 7
Recognition Sequence	GGTCCGCGACGTACGCGCACTT		SEQ ID NO: 8
	F8R3	F8R4	
	Half-Site	Half-Site	
F8R 3-4	GCAGCAGCAGCAAGCGGGACAC		SEQ ID NO: 9
Recognition Sequence	CGTCGTCGTGCGGCCCTGTG		SEQ ID NO:10
	F8R9	F8R10	
	Half-Site	Half-Site	
F8R 9-10	CAGGATTGTGTGCAACTTCGGC		SEQ ID NO:11
Recognition Sequence	GTCCTAACACACGTTGAAGCCG		SEQ ID NO:12
	F8R11	F8R12	
	Half-Site	Half-Site	
F8R 11-12	CTGCAGGCTGTACAAGGCTTCT		SEQ ID NO:13
Recognition Sequence	GACGTCCGACATGTTCCGAAGA		SEQ ID NO:14
	F8R13	F8R14	
	Half-Site	Half-Site	
F8R 13-14	GGAGGACGGGTACACGCCTTC		SEQ ID NO:15
Recognition Sequence	CCTCCTGCCCATGGTGCGGAAG		SEQ ID NO:16
	F8R15	F8R16	
	Half-Site	Half-Site	
F8R 15-16	GGCCGTCAGGTACTCAATAACC		SEQ ID NO:17
Recognition Sequence	CCGGCAGTCCATGAGTTATTGG		SEQ ID NO:18

Fig. 2

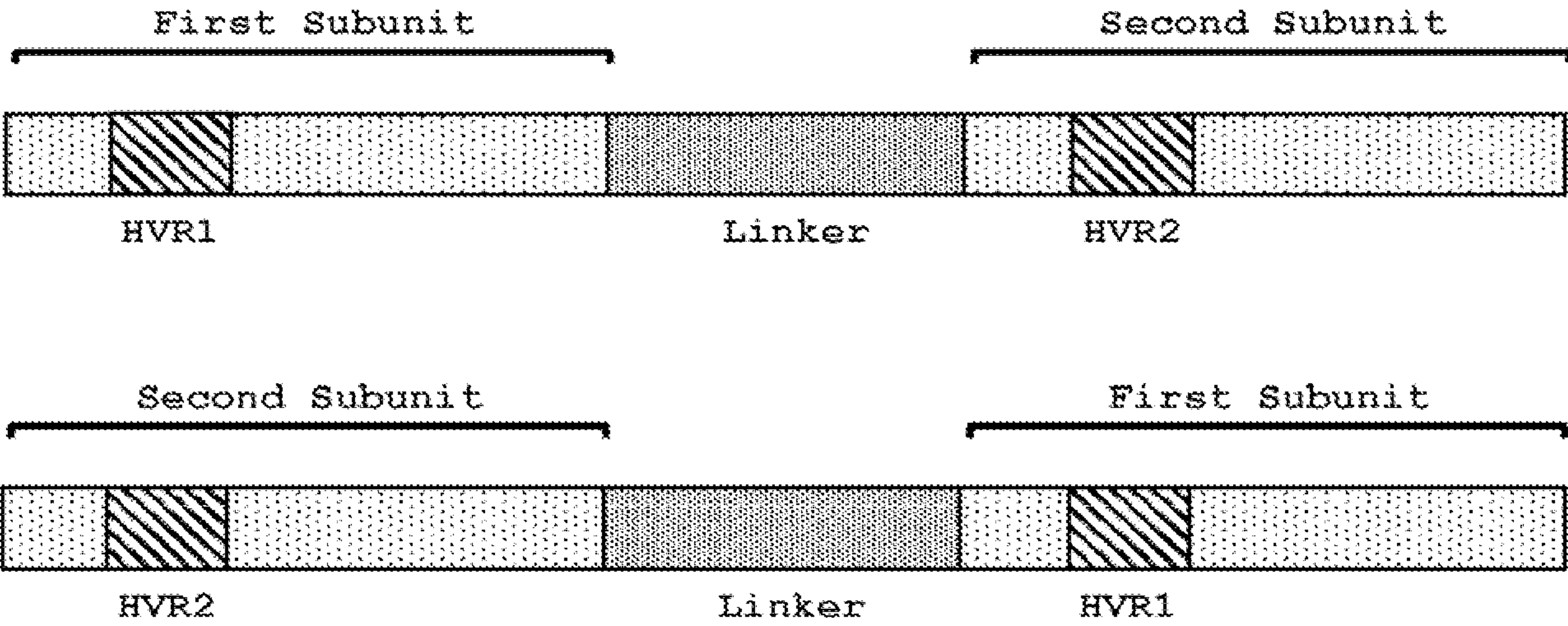


Fig. 3

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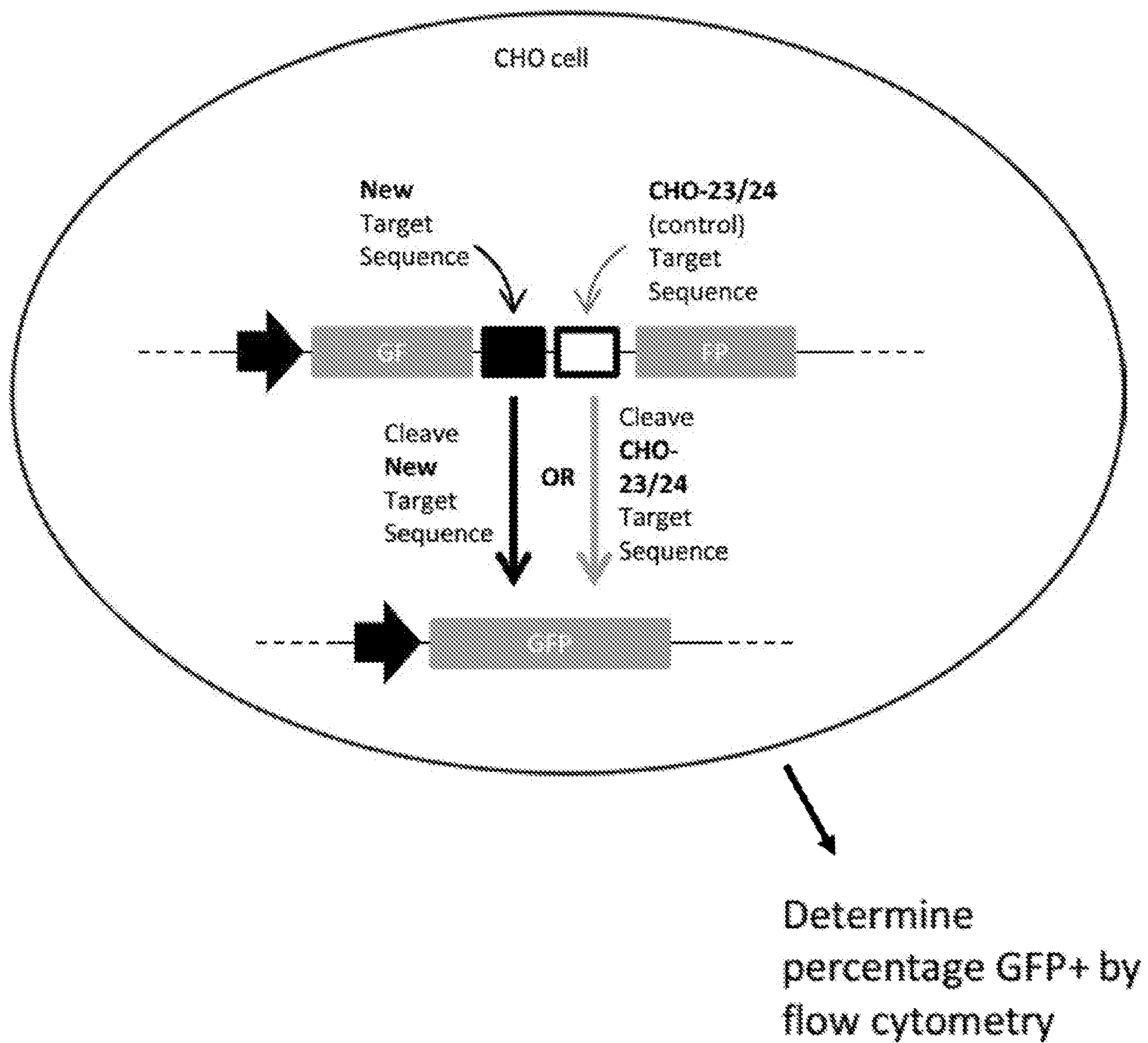
**Fig. 4**

Fig. 5A

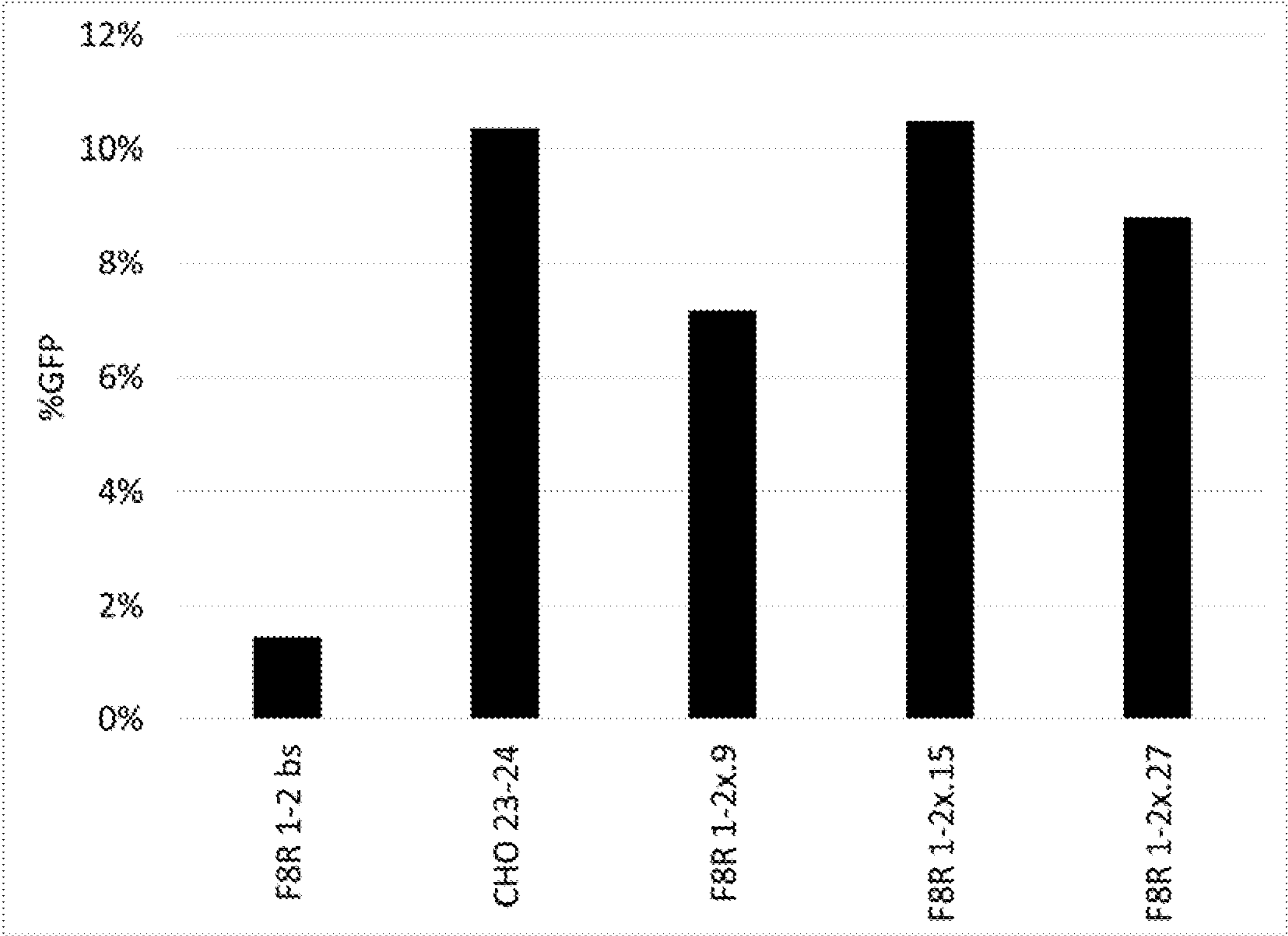
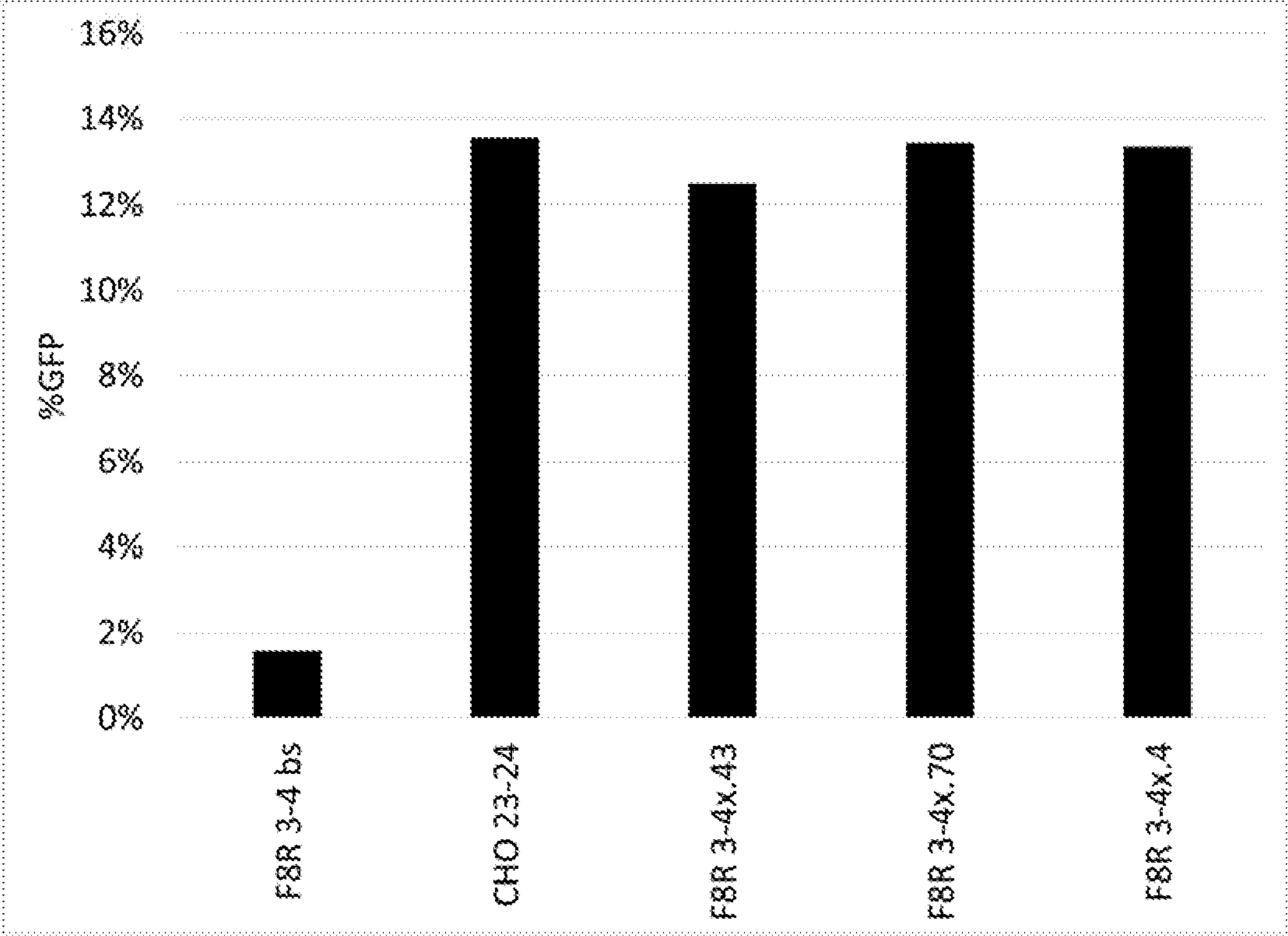


Fig. 5B



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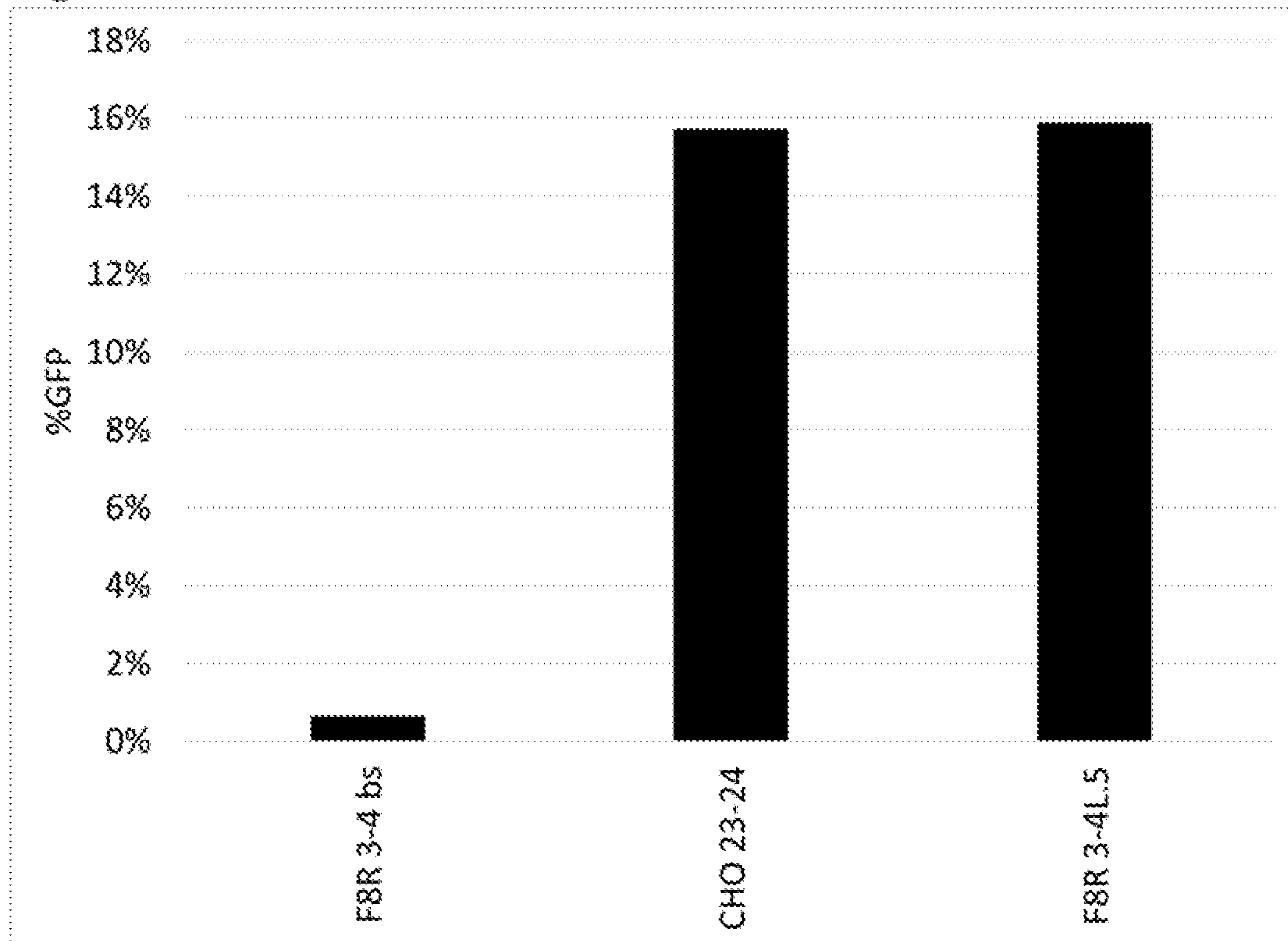
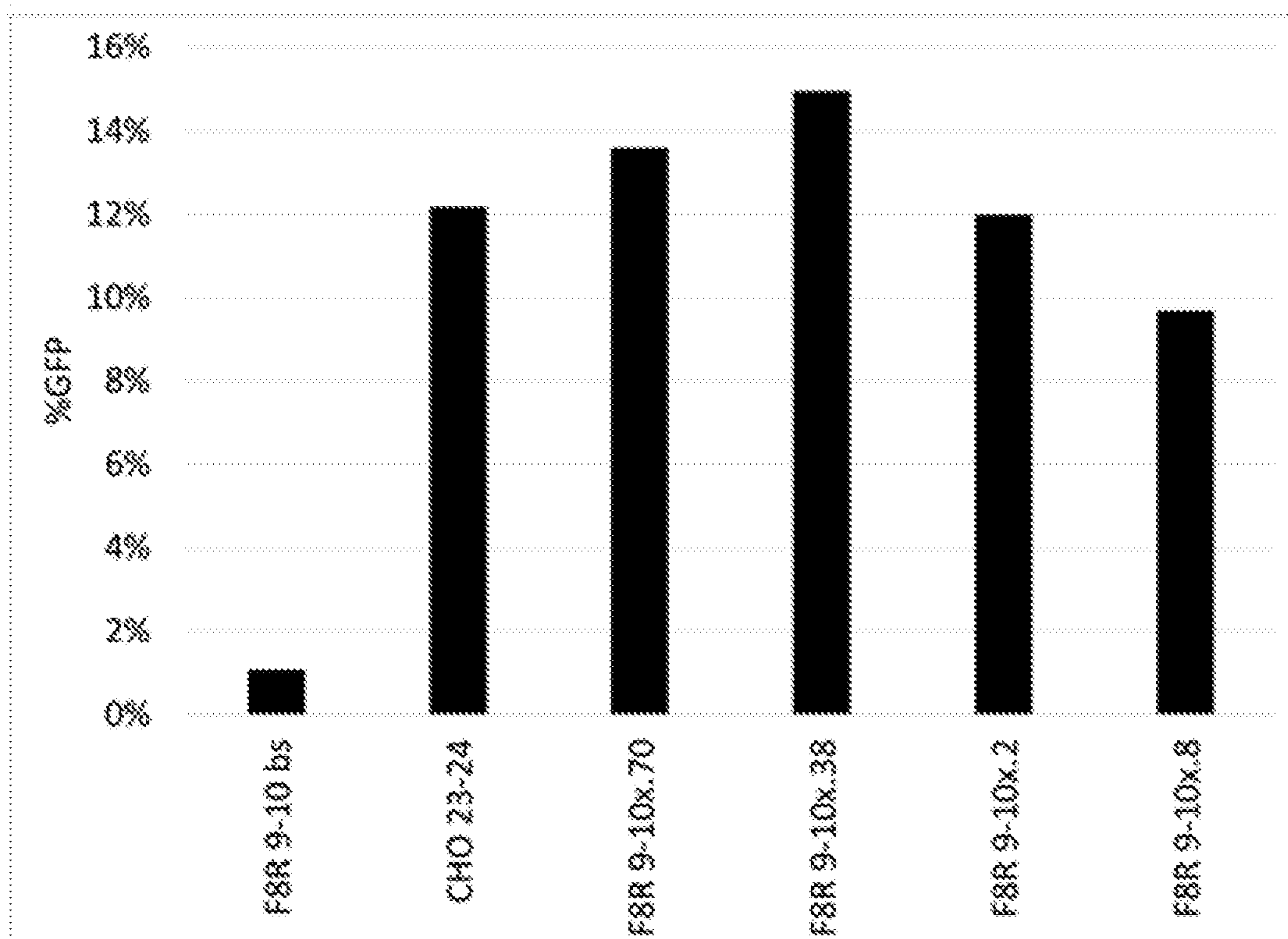
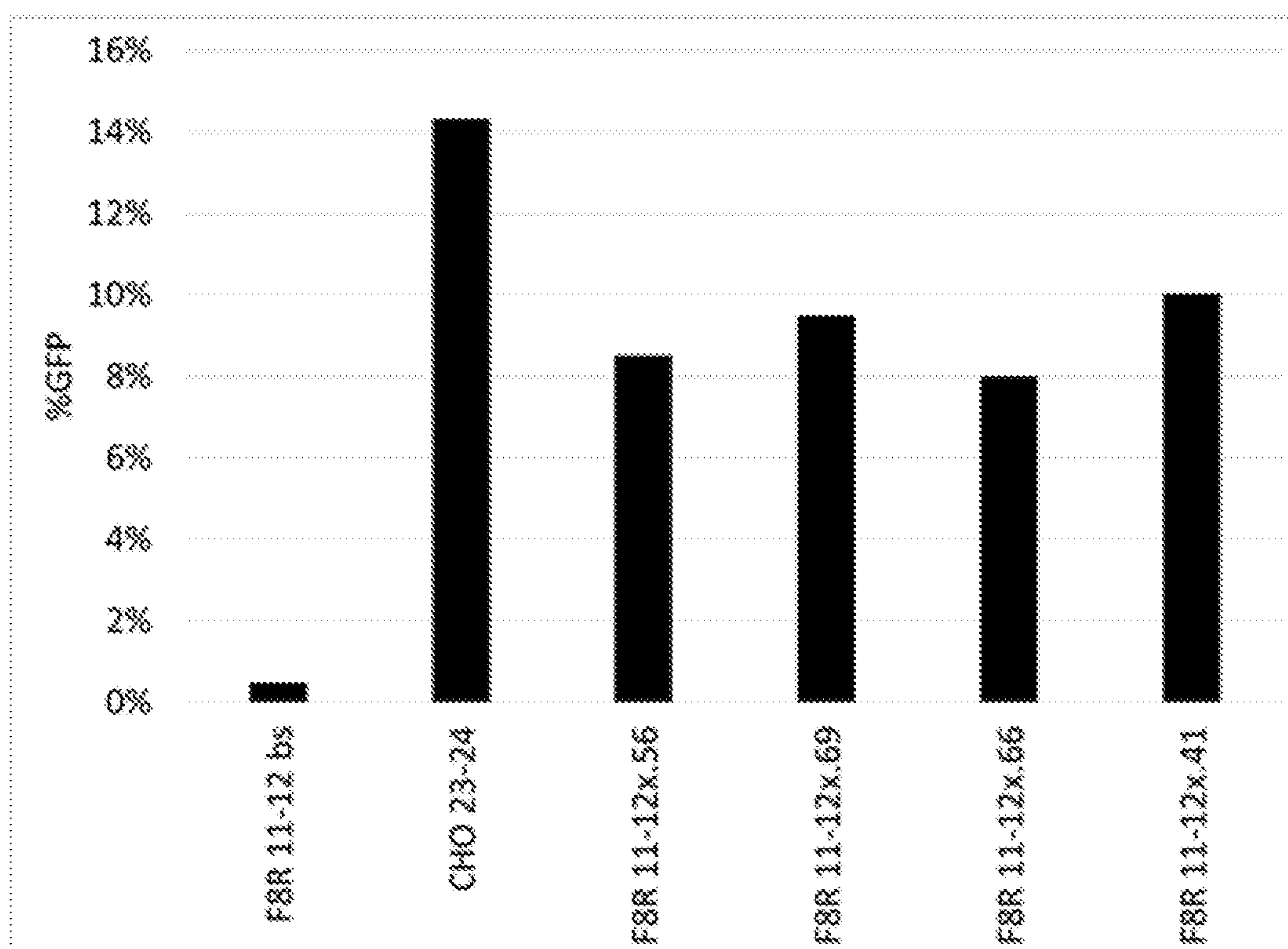
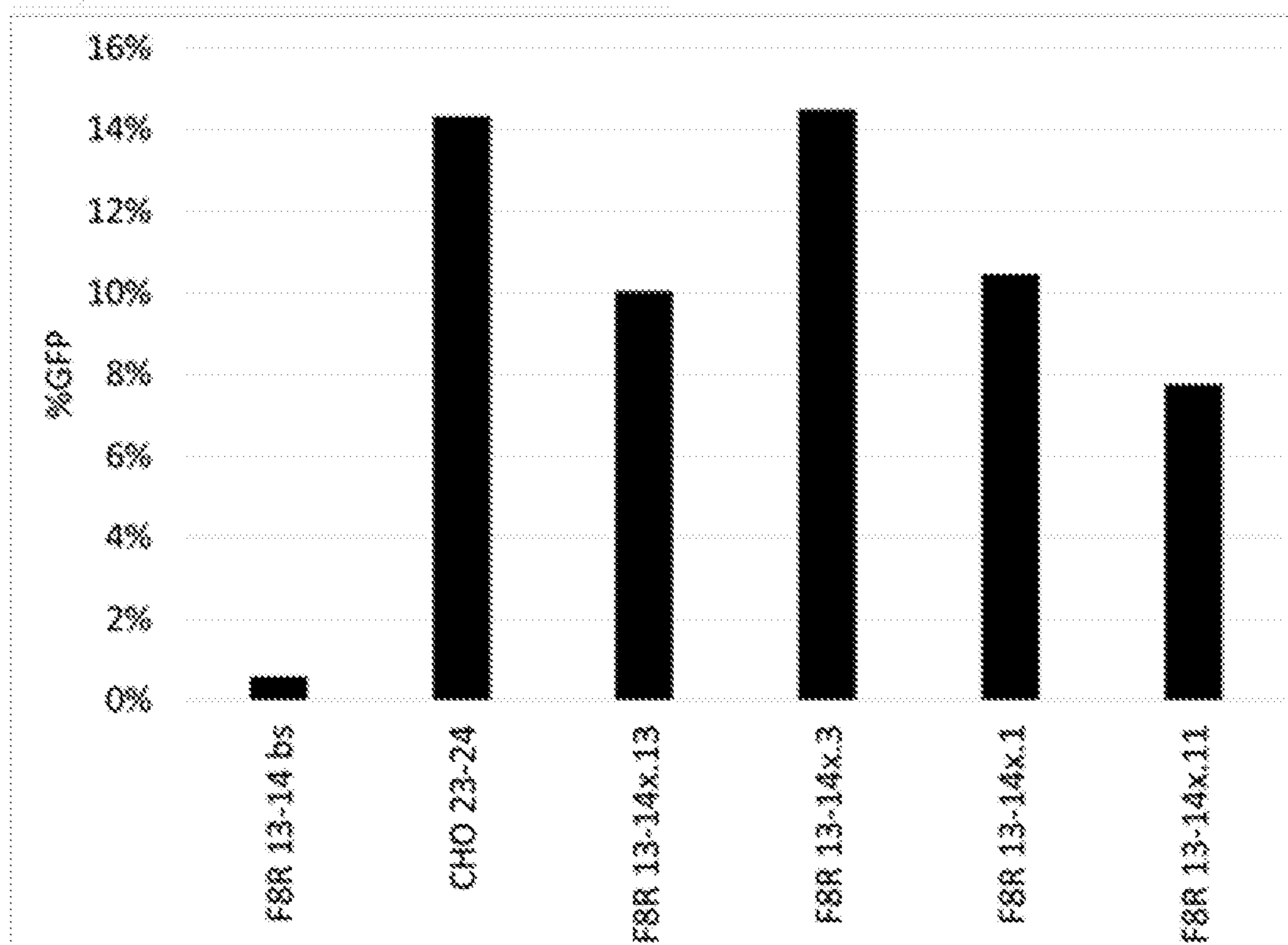
Fig. 5C**Fig. 5D**

Fig. 5E

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**Fig. 5F**

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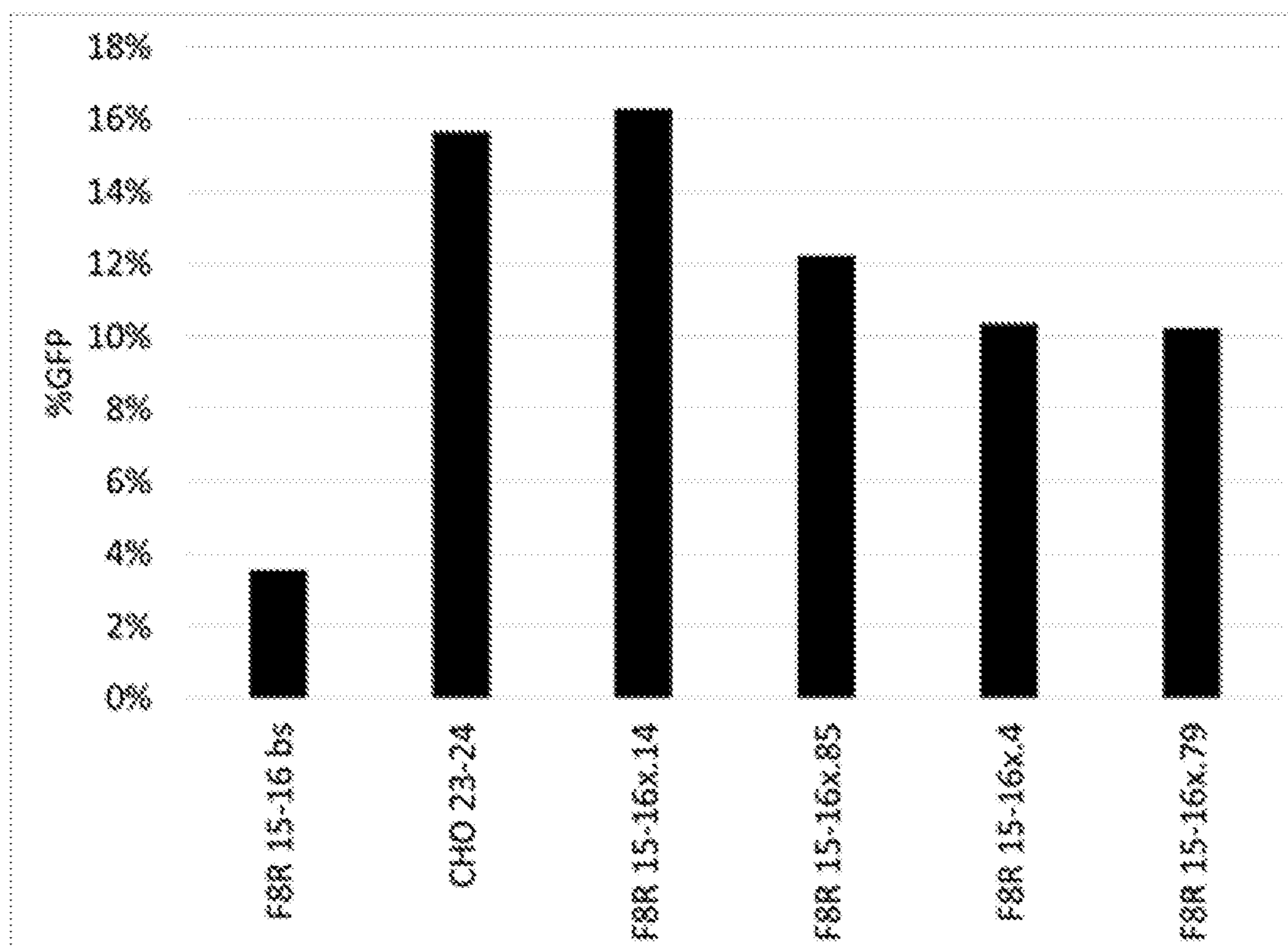
Fig. 5G

Fig. 6A

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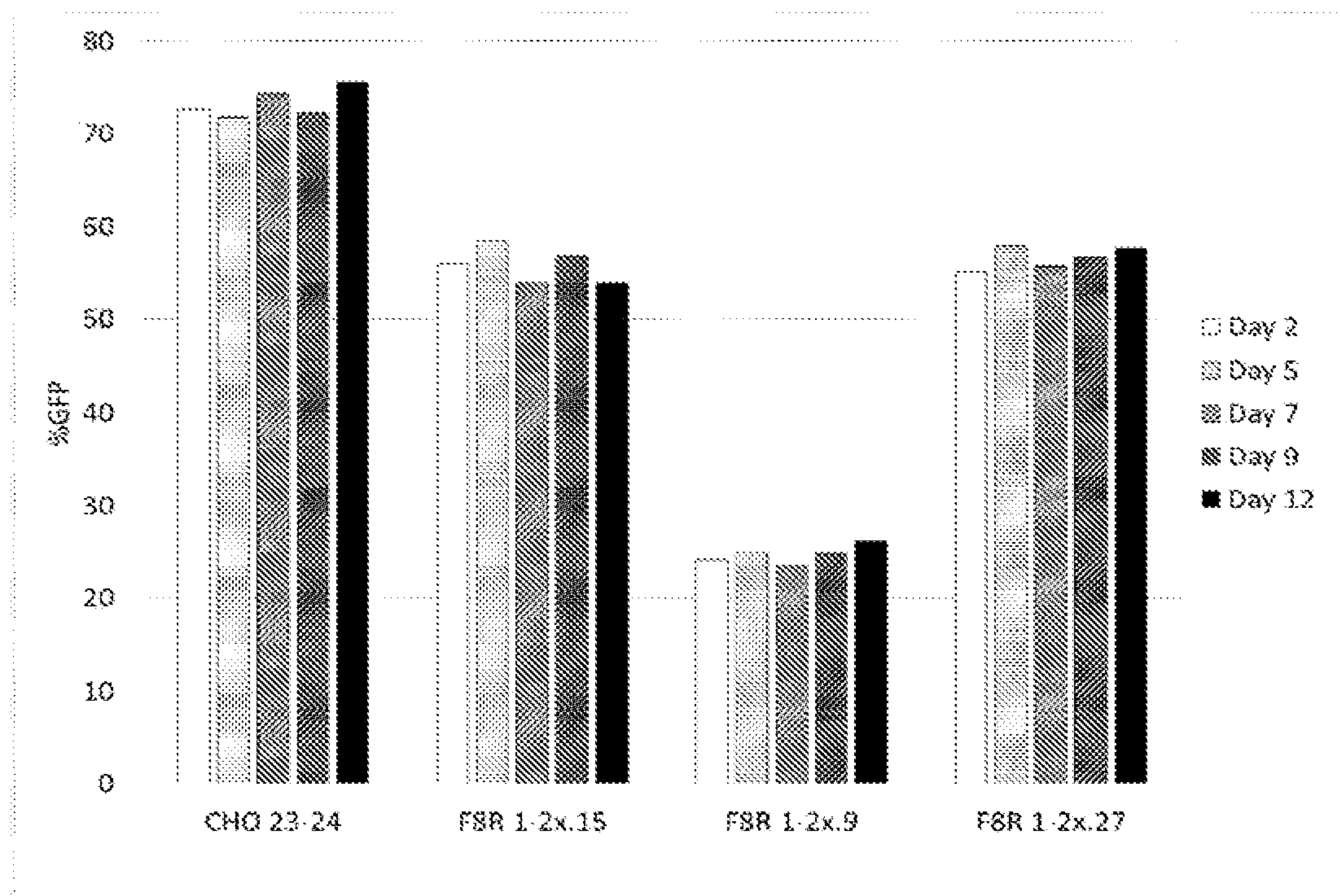
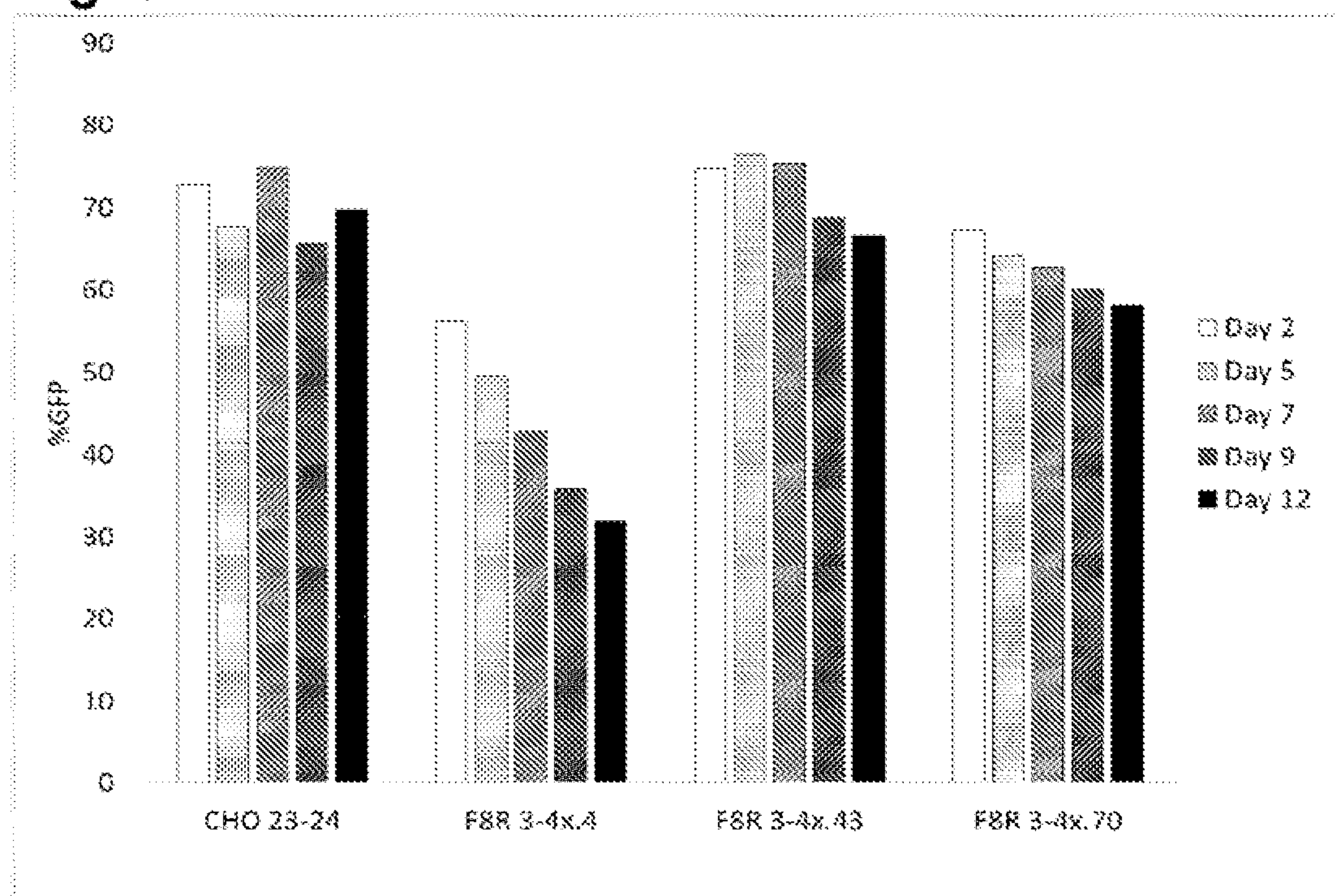
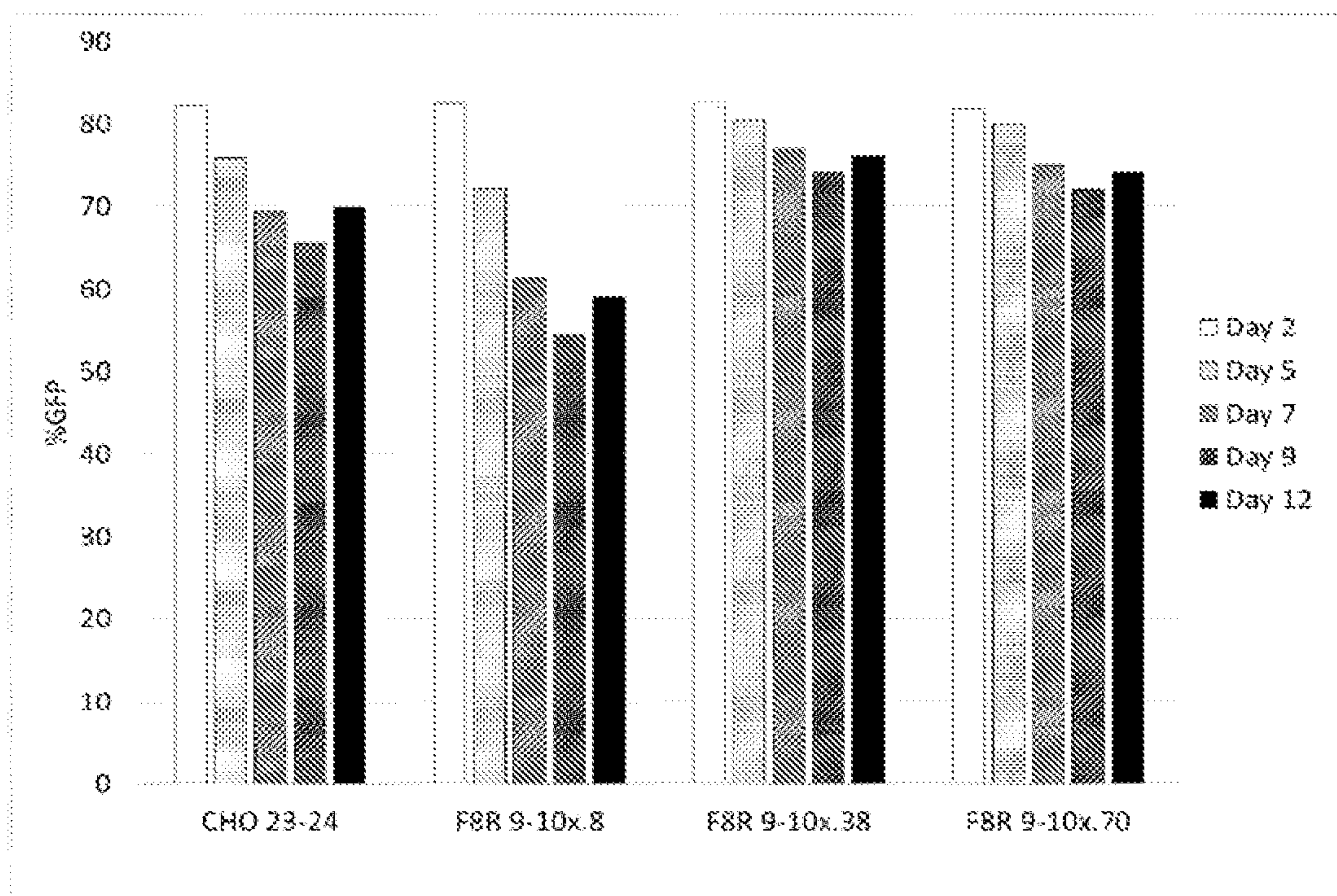
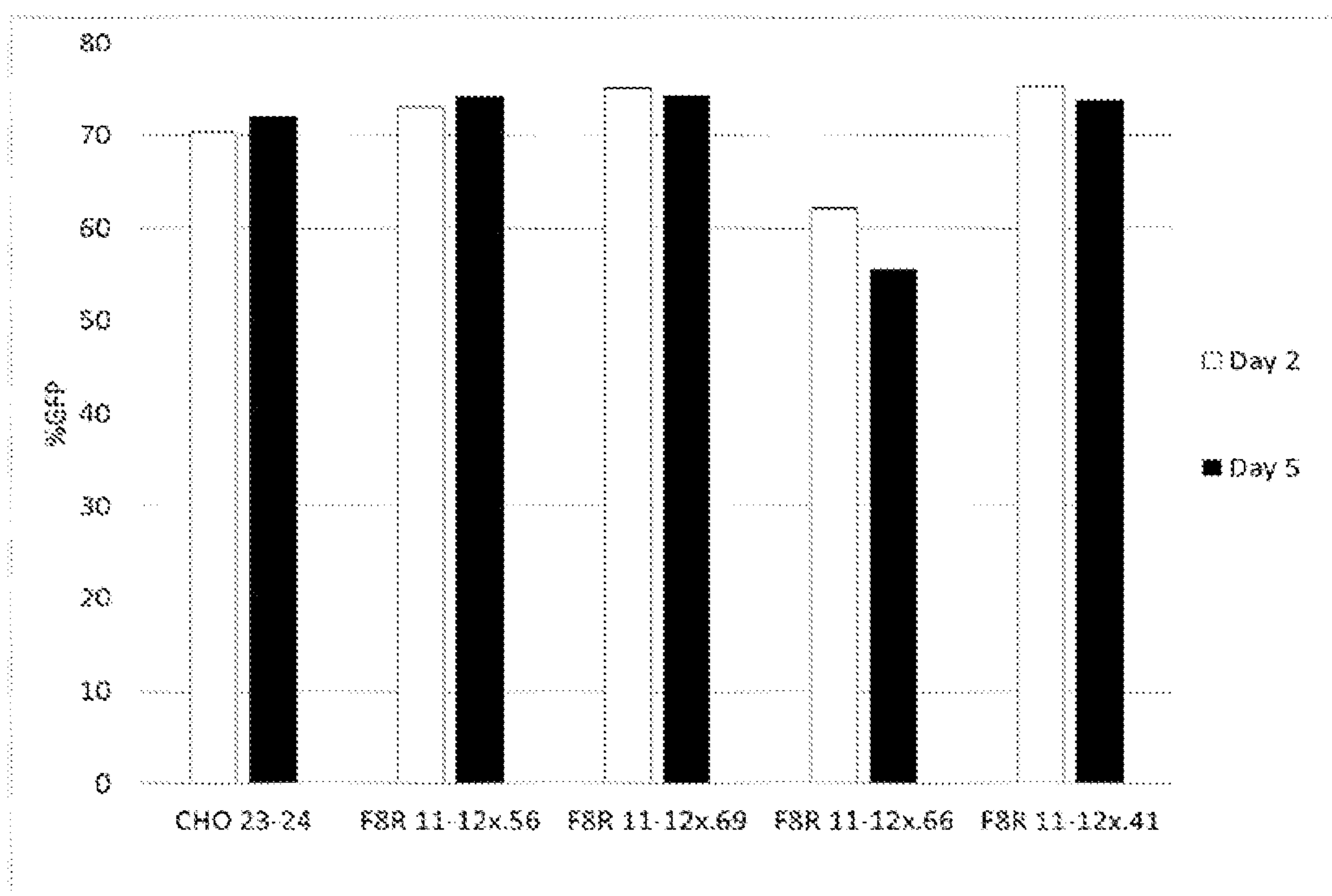
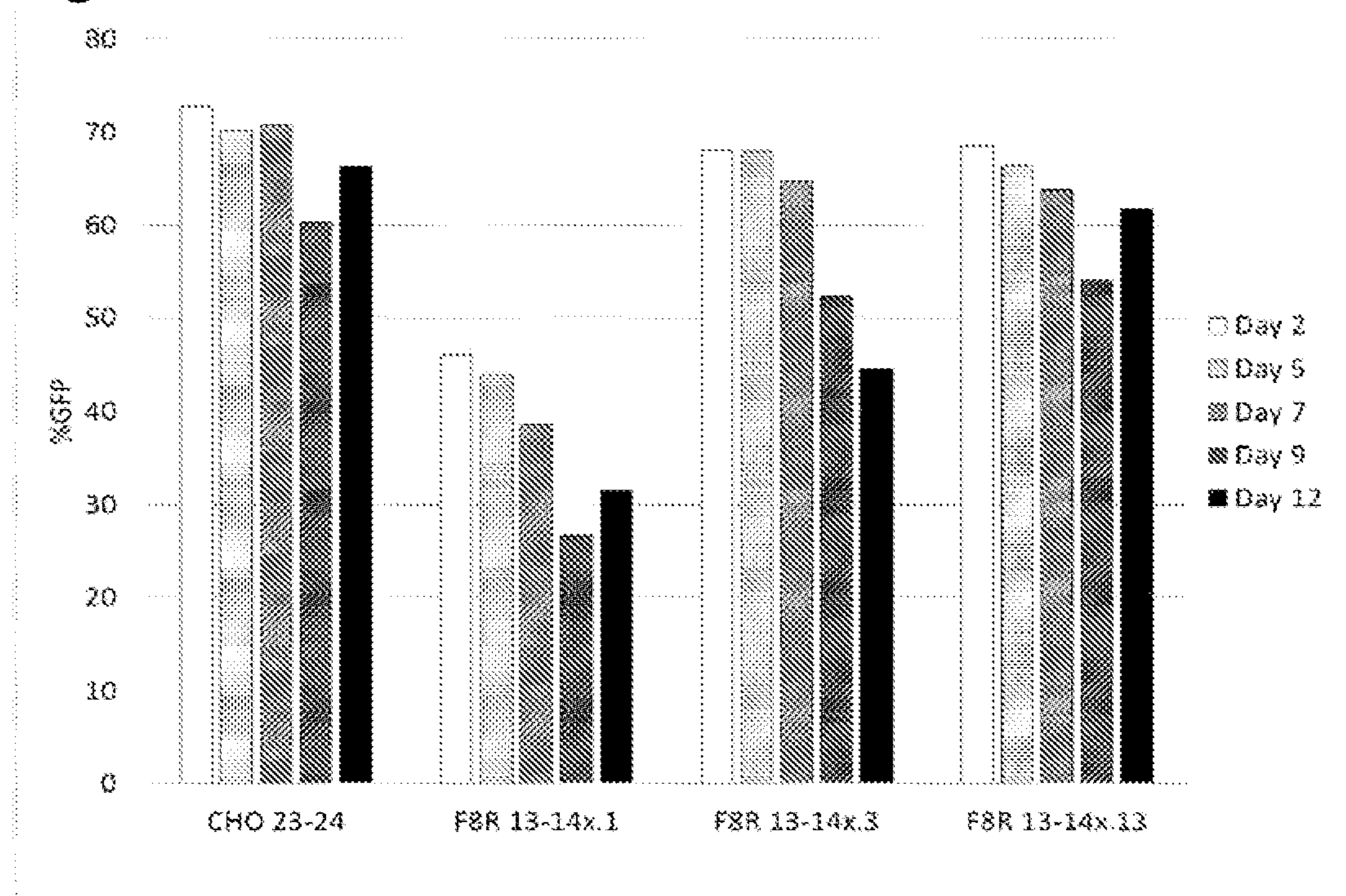
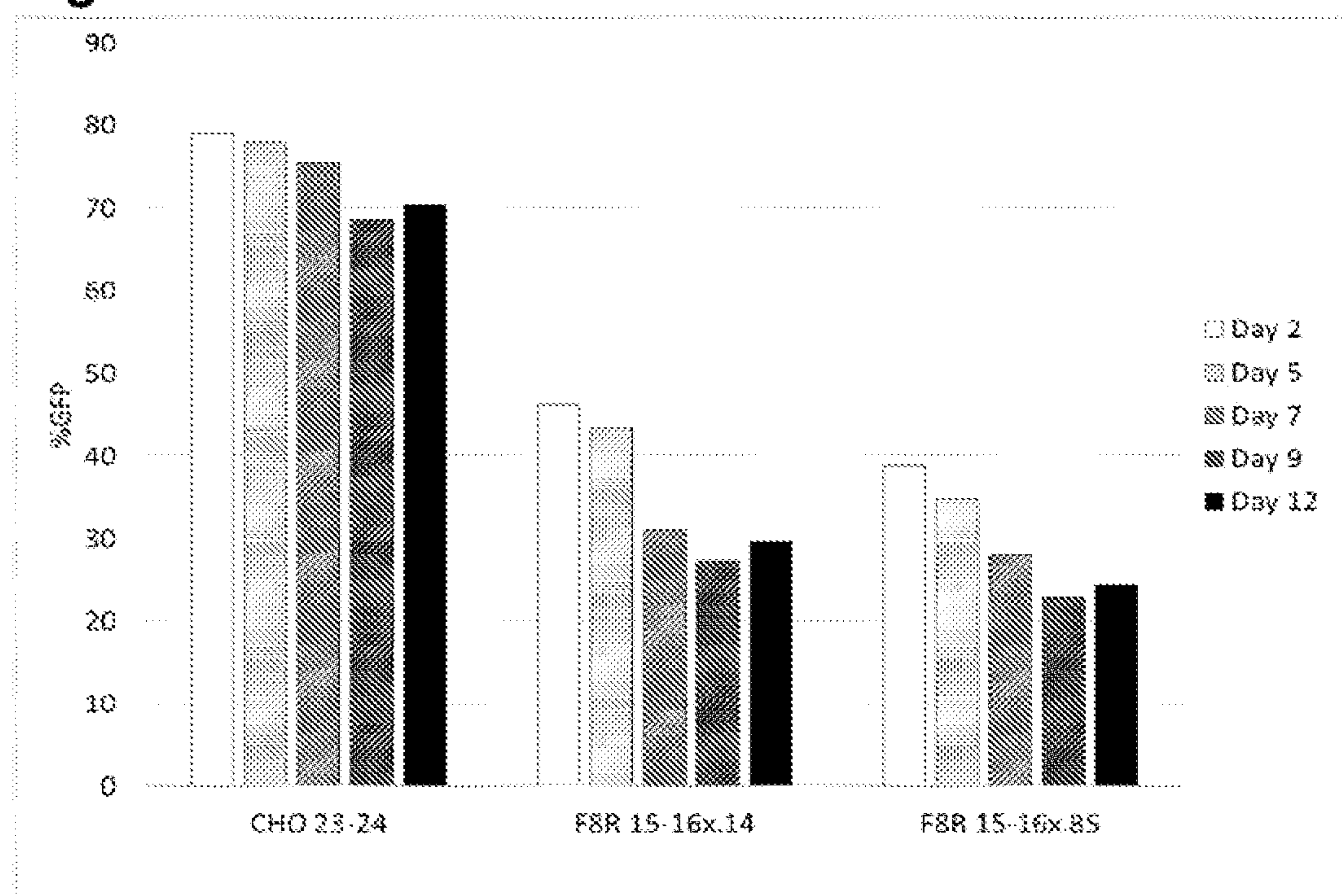
**Fig. 6B**

Fig. 6C

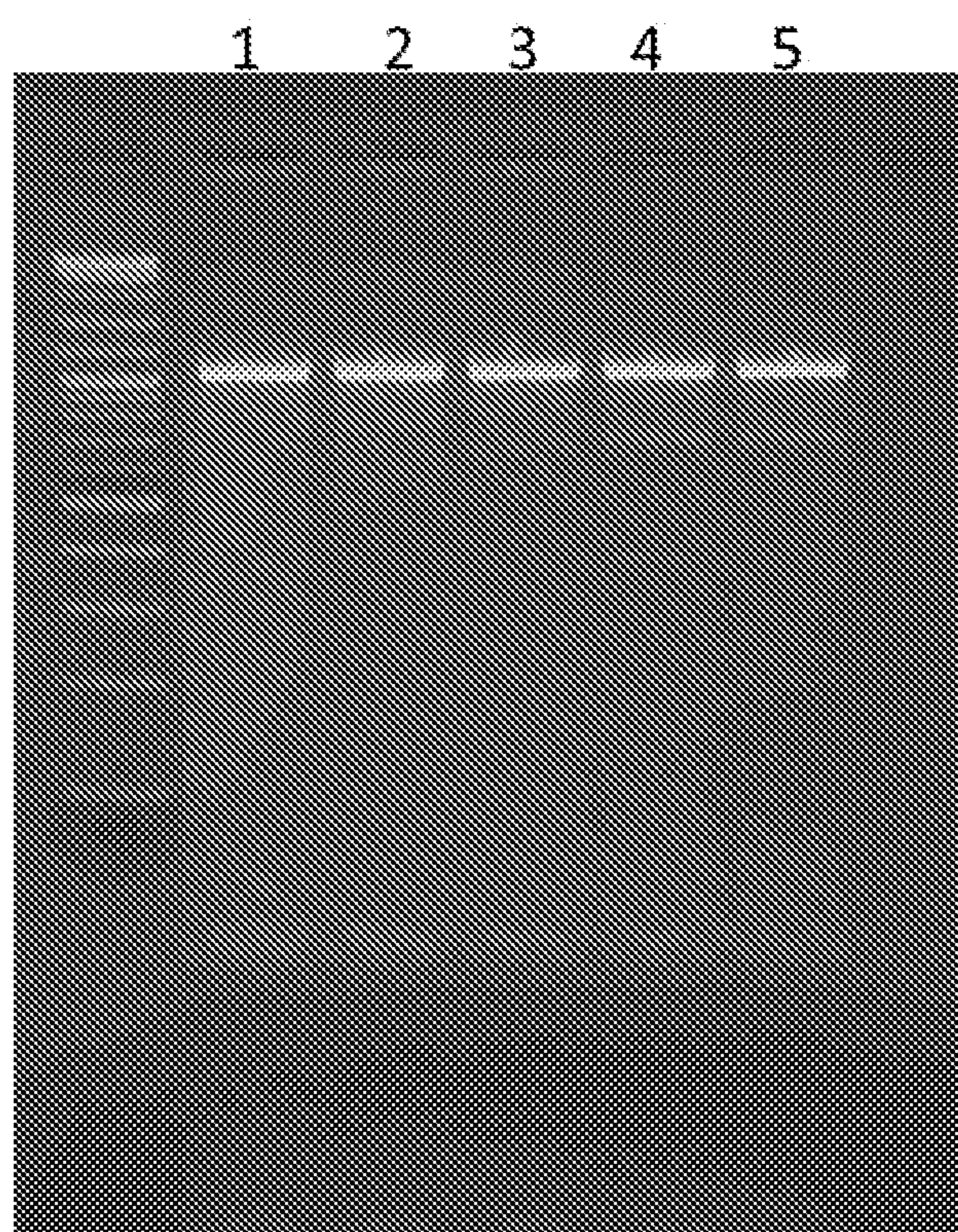
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**Fig. 6D**

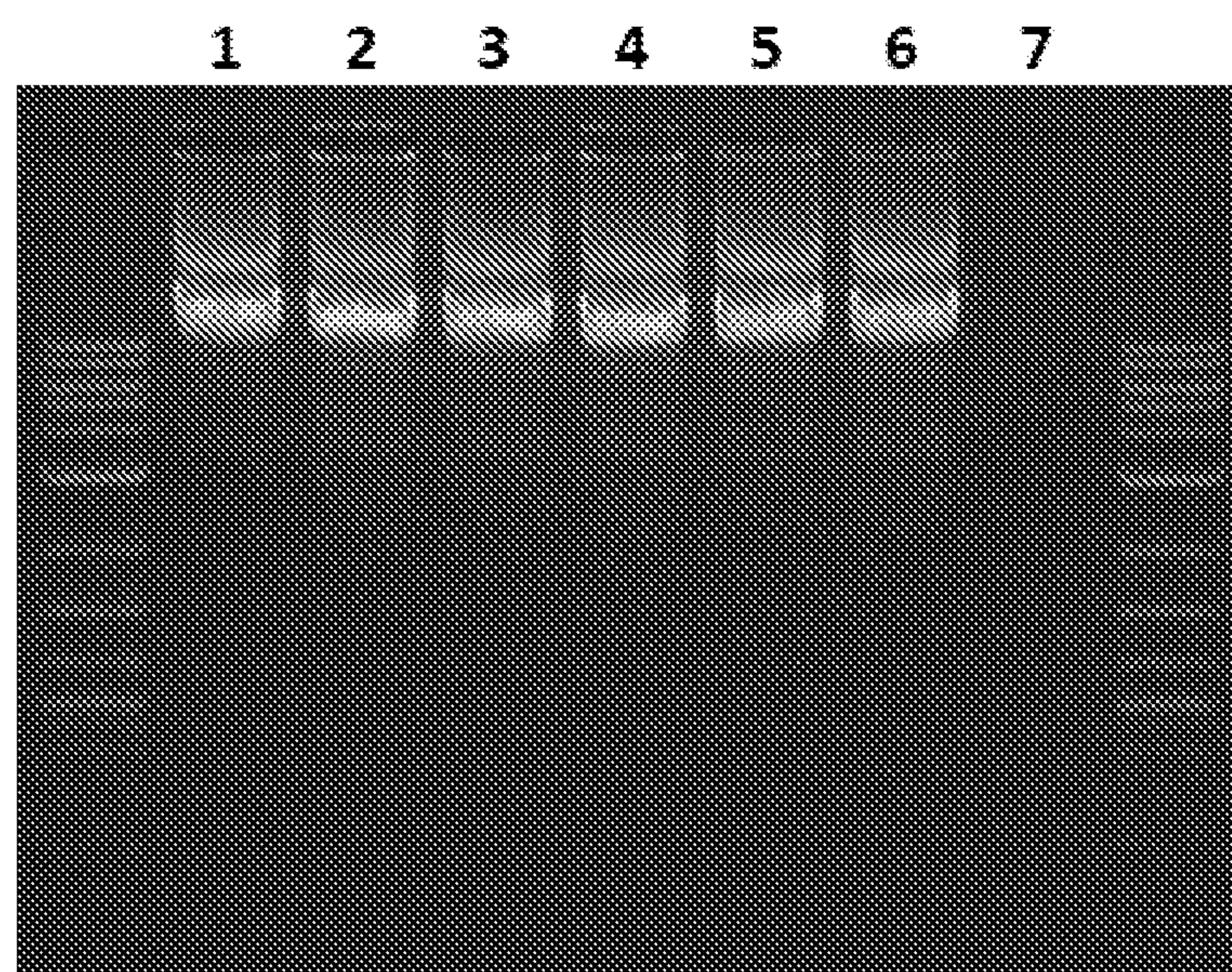
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Fig. 6E**Fig. 6F**

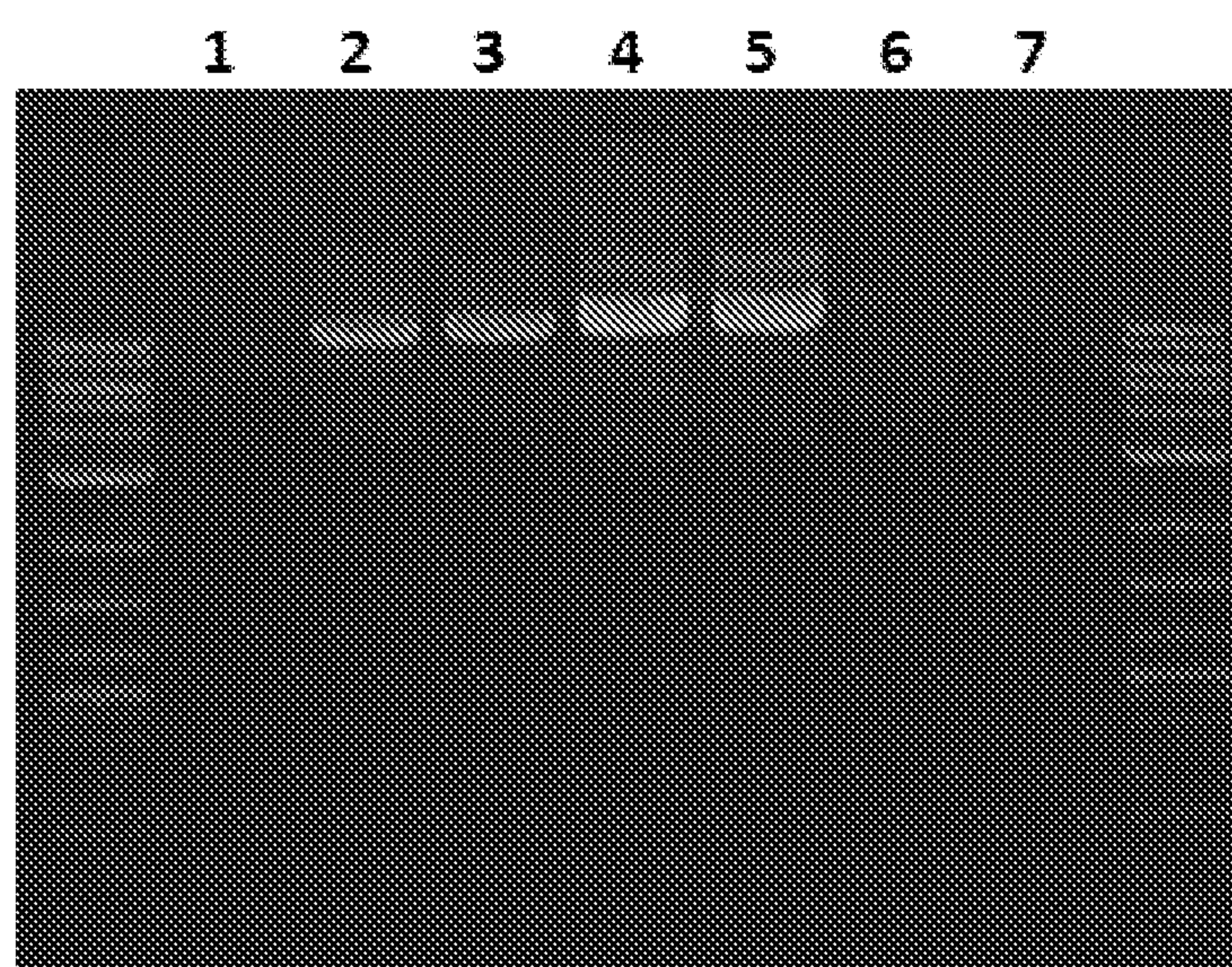
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**Fig. 7**

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Fig. 8A

Primers H1R and H1F

Fig. 8B

Primers H1F and H2/3R

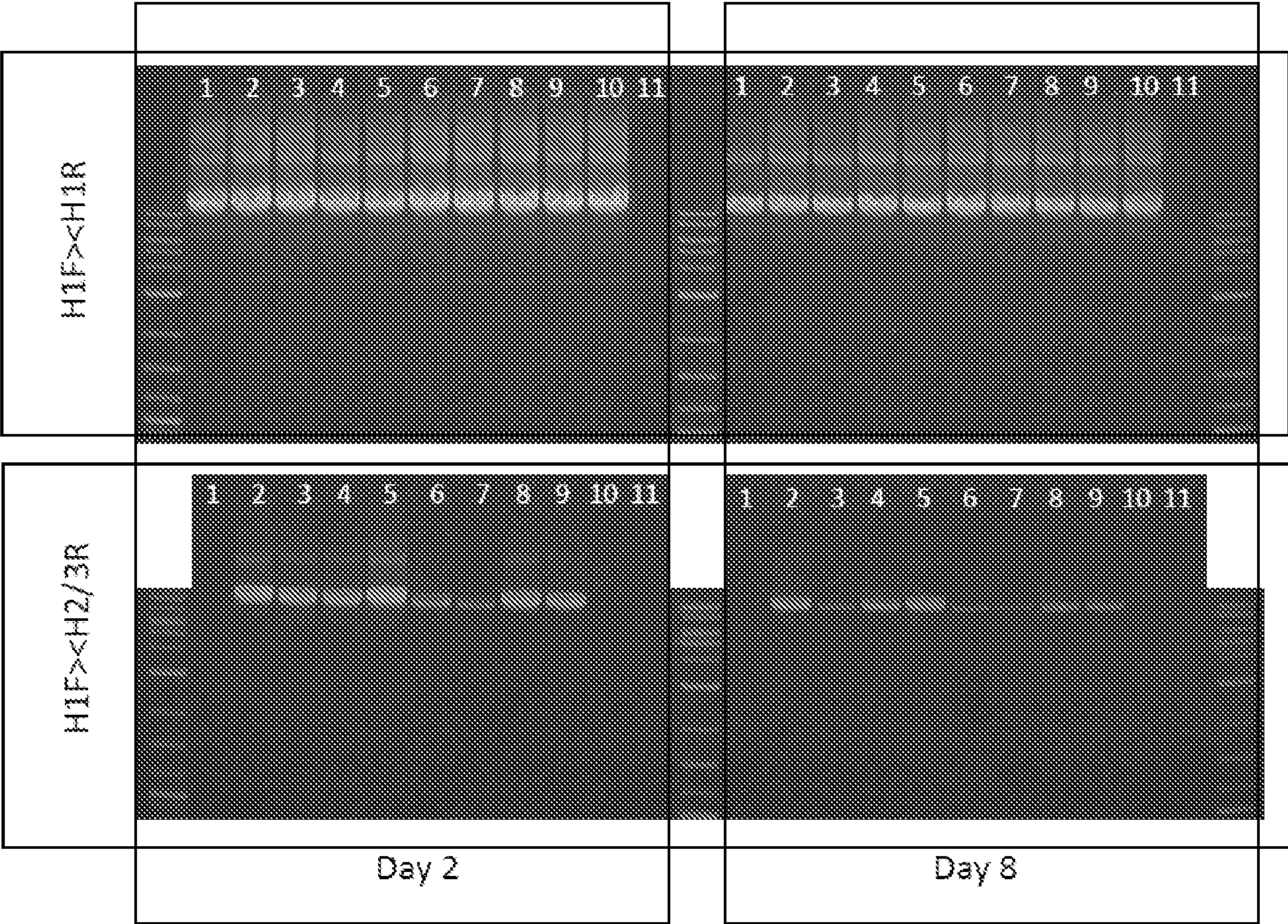


Fig. 9

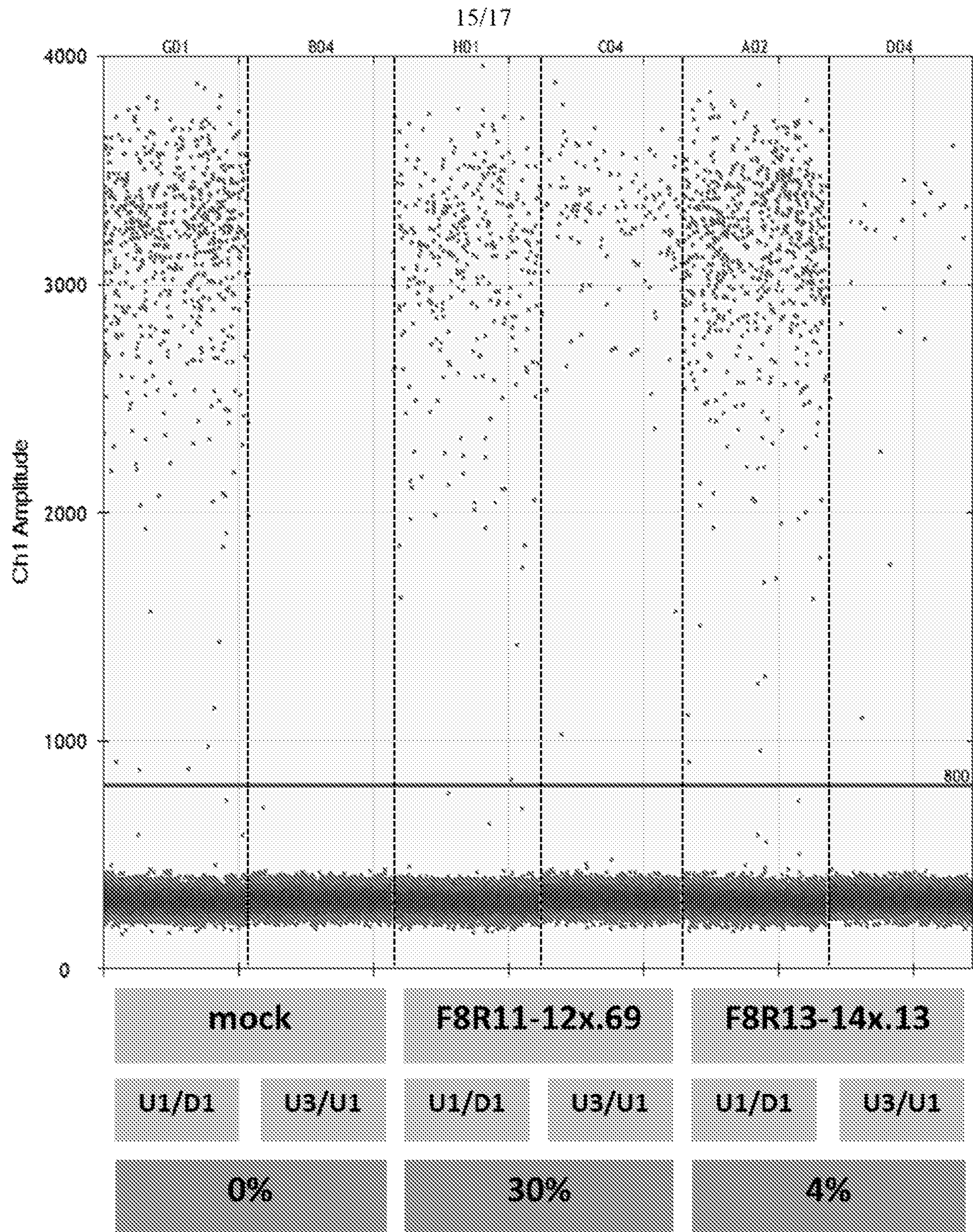
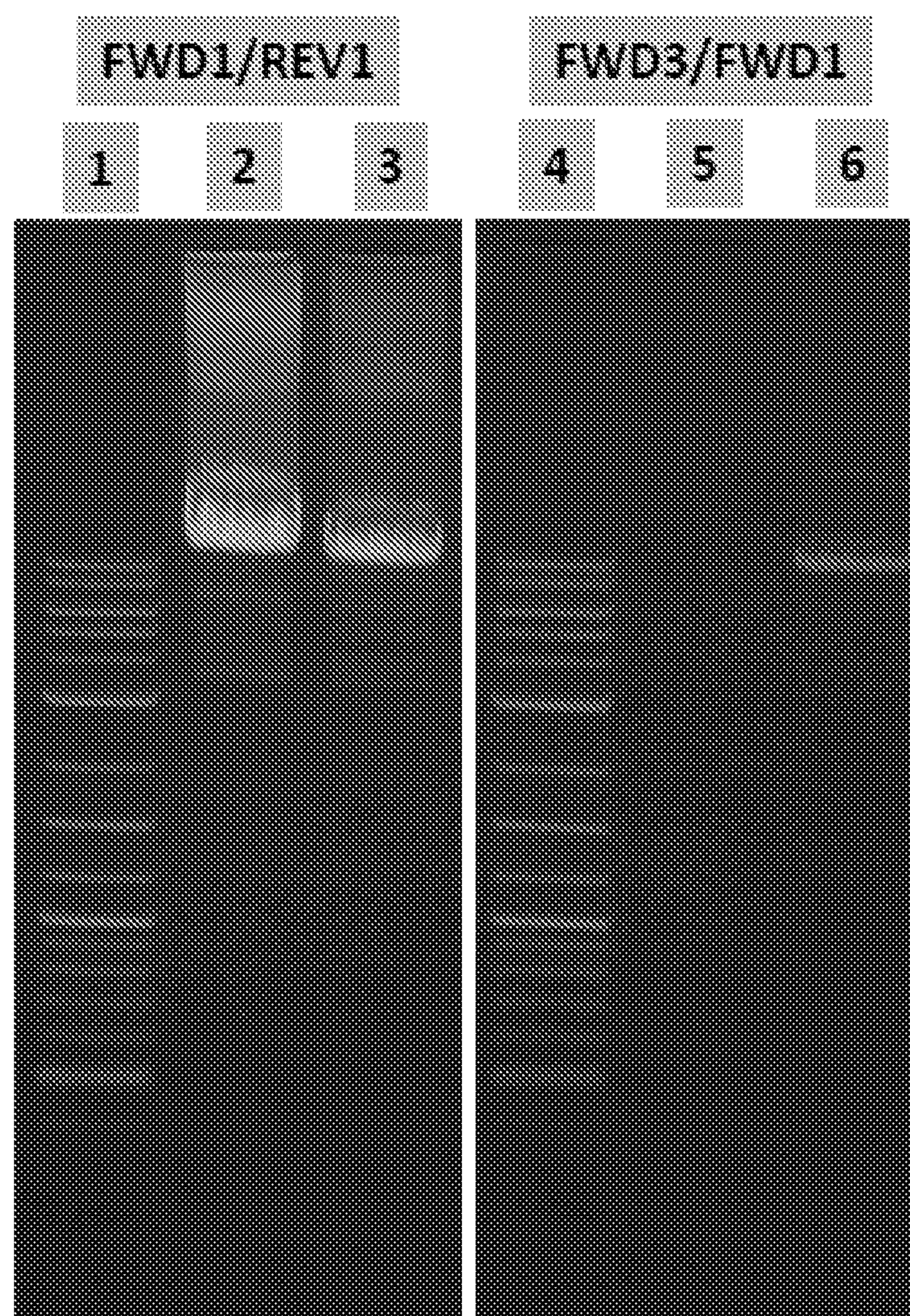


Fig. 10

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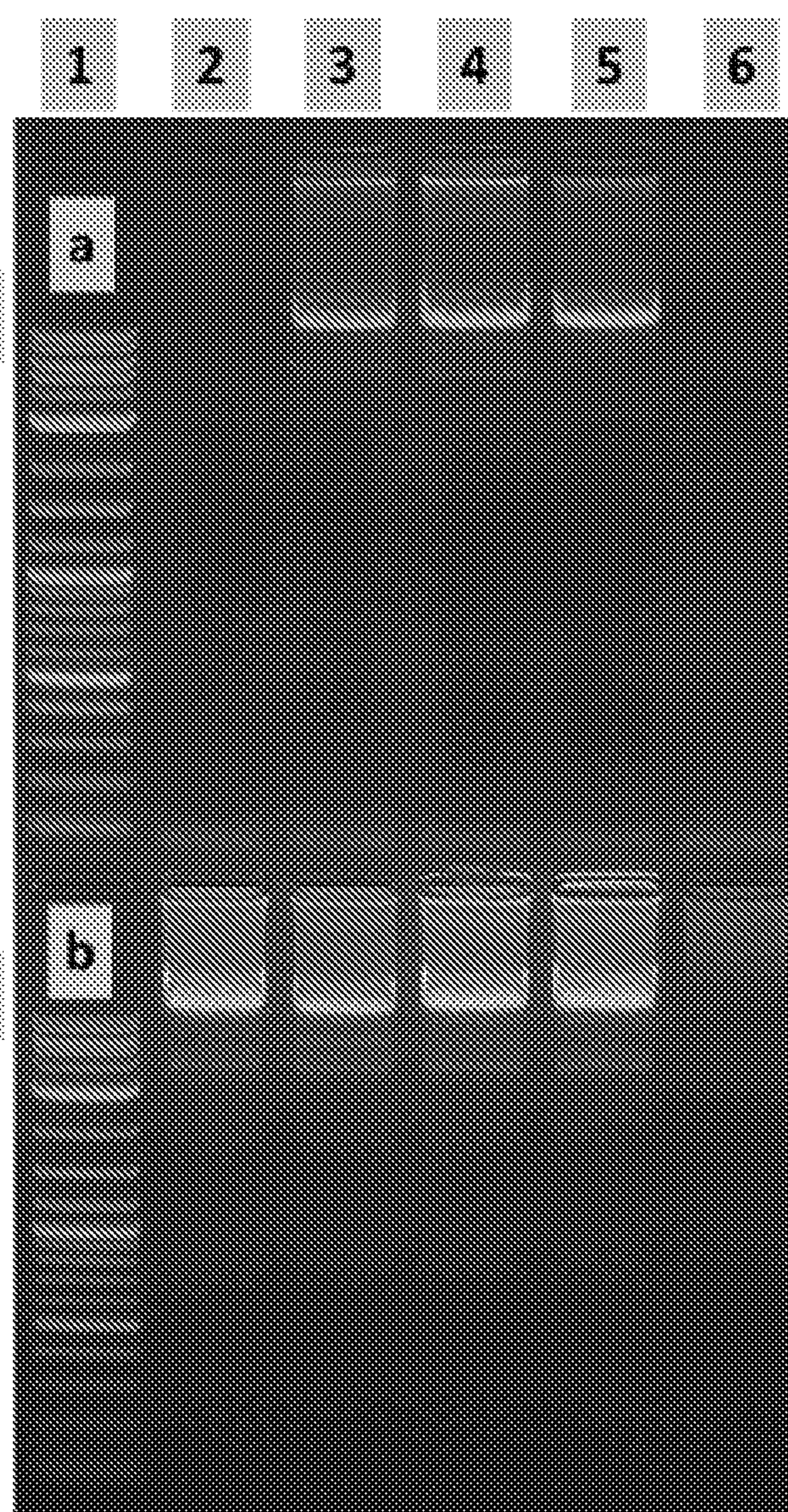
lanes 1 and 4: molecular weight standard

lanes 2 and 5: human T-cells

lanes 3 and 6: human T-cells treated with F8R3-4x.43 nuclease

Fig. 11

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Fig. 12A**H1U/H1D****Fig. 12B****H3D/H1D**

lanes 1a and 1b: molecular weight standard

lanes 2a and 2b: patient T-cells treated with GFP

lanes 3a and 3b: patient T-cells treated with F8R3-4x.43 nuclease

lanes 4a and 4b: patient T-cells treated with F8R11-12x.69 nuclease

lanes 5a and 5b: patient T-cells treated with F8R15-16x.14 nuclease

lanes 6a and 6b: no-template control

Fig. 1A

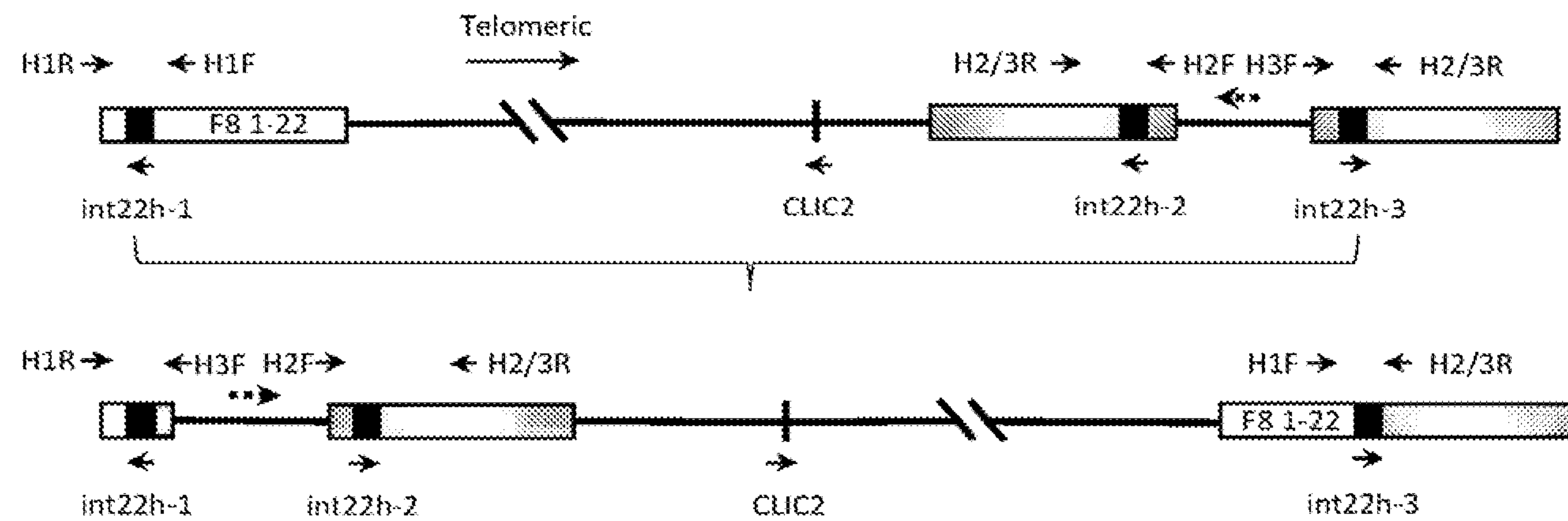


Fig. 1B

