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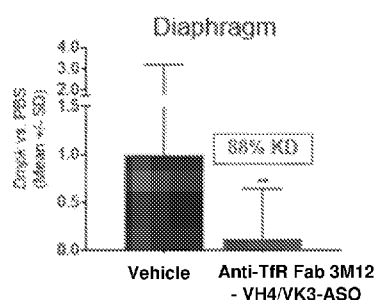


FIG. 1D

(57) Abstract: The present application relates to oligonucleotides (e.g., antisense oligonucleotides such as gapmers) designed to target FXN RNAs and targeting complexes for delivering the oligonucleotides to cells (e.g., muscle cells) and uses thereof, particularly uses relating to treatment of disease. In some embodiments, the muscle-targeting agent specifically binds to an internalizing cell surface receptor on muscle cells. In some embodiments, the molecular payload increases expression or activity of a FXN allele comprising a disease-associated- repeat.



MUSCLE TARGETING COMPLEXES AND USES THEREOF FOR TREATING FRIEDREICH'S ATAXIA

RELATED APPLICATIONS

[0001] This application claims priority under 35 U.S.C. § 119(e) to U.S. Provisional Application No. 63/212,816, entitled "MUSCLE-TARGETING COMPLEXES AND USES THEREOF FOR TREATING FRIEDREICH'S ATAXIA", filed on June 21, 2021, the contents of which are incorporated herein by reference in their entirety.

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

[0002] 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 June 17, 2022, is named D082470049WO00-SEQ-ZJG and is 191,024 bytes in size.

FIELD OF THE INVENTION

[0003] The present application relates to oligonucleotides designed to target FXN RNAs and targeting complexes for delivering the oligonucleotides to cells (e.g., muscle cells) and uses thereof, particularly uses relating to treatment of disease.

BACKGROUND

[0004] Friedreich's ataxia is a rare, autosomal recessive disease that leads to progressive damage of muscle tissues and the nervous system. Hallmarks of the disease include severe heart conditions, *e.g.*, hypertrophic cardiomyopathy, myocardial fibrosis, and heart failure, and degeneration of nerve fibers in the spinal cord and peripheral nervous system. Friedreich's Ataxia results from a mutation in the FXN gene, which codes for frataxin, a protein proposed to function in iron homeostasis. Specifically, subjects with the disease have an expanded trinucleotide GAA sequence that leads to decreased levels of frataxin. Friedreich's ataxia is the most common form of hereditary ataxia, with an incidence of about 1 in every 50,000 people. In the most severe cases, subjects with the disease may be unable to walk freely by the age of 10-20 and many subjects experience shortened life expectancy. In Friedreich's ataxia, the reduction of FXN expression may be attributable to epigenetic silencing and/or from a decreased ability to splice out the first intron of FXN pre-mRNA, which contains an expanded GAA repeat. With

the exception of supportive care to combat symptoms of the disease, there are no current and effective treatments available for Friedreich's ataxia.

SUMMARY

[0005] According to some aspects, the disclosure provides oligonucleotides designed to target FXN RNAs. In some embodiments, the disclosure provides oligonucleotides complementary with FXN RNA that are useful for increasing levels of functional FXN by blocking FXN RNA containing expanded GAA repeats, *e.g.*, in a subject having or suspected of having Friedreich's ataxia. In some embodiments, the oligonucleotides are designed to direct RNase H mediated degradation of the FXN RNA containing expanded GAA repeats. In some embodiments, the oligonucleotides are designed to inhibit formation of an RNA loop (R-loop) by the FXN RNA containing expanded GAA repeats with chromosomal DNA. In some embodiments, the oligonucleotides are designed to enhance FXN protein level by inhibiting formation of an RNA loop (R-loop) between the FXN RNA containing expanded GAA repeats and chromosomal DNA. In some embodiments, the oligonucleotides are designed to have desirable bioavailability and/or serum-stability properties. In some embodiments, the oligonucleotides are designed to have desirable binding affinity properties. In some embodiments, the oligonucleotides are designed to have desirable toxicity profiles. In some embodiments, the oligonucleotides are designed to have low-complement activation and/or cytokine induction properties.

[0006] In some embodiments, oligonucleotides provided herein are conjugated to other molecules, *e.g.*, targeting agents, *e.g.*, muscle targeting agents. Accordingly, in some aspects, the disclosure provides complexes that target specific cell types for purposes of delivering the oligonucleotides to those cells. For example, in some embodiments, the disclosure provides complexes that target muscle cells for purposes of delivering oligonucleotides to muscle cells. In some embodiments, complexes provided herein are particularly useful for delivering molecular payloads that increase the expression or activity of functional FXN protein by reducing the level of FXN RNA containing an expanded disease-associated-repeat, *e.g.*, in a subject having or suspected of having Friedreich's ataxia. In some embodiments, complexes provided herein comprise muscle-targeting agents (*e.g.*, muscle targeting antibodies) that specifically bind to receptors on the surface of muscle cells for purposes of delivering molecular payloads to the muscle cells. In some embodiments, the complexes are taken up into the cells via a receptor mediated internalization, following which the molecular payload may be released to perform a function inside the cells. For example, complexes engineered to deliver

oligonucleotides may release the oligonucleotides such that the oligonucleotides can block mutant FXN in the muscle cells. In some embodiments, the oligonucleotides are released by endosomal cleavage of covalent linkers connecting oligonucleotides and muscle-targeting agents of the complexes.

[0007] Some aspects of the present disclosure provide complexes comprising a muscle-targeting agent covalently linked to an oligonucleotide configured for increasing FXN expression, wherein the oligonucleotide comprises a region of complementarity to a repeat region of an FXN RNA containing disease-associated expanded GAA repeats, wherein the repeat region comprises a target sequence as set forth in any one of SEQ ID NOs: 162-164, and wherein the region of complementarity is at least 12 nucleotides in length.

[0008] In some embodiments, the muscle-targeting agent is an anti-transferrin receptor 1 (TfR1) antibody.

[0009] In some embodiments, the oligonucleotide comprises at least 16 consecutive nucleotides of any one of SEQ ID NOs: 165-176, wherein each of the Us are optionally and independently Ts. In some embodiments, the oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 165-176, and wherein each of the Us are optionally and independently Ts.

[00010] In some embodiments, the oligonucleotide comprises a 5'-X-Y-Z-3' configuration, wherein X comprises 3-5 linked nucleosides, wherein at least one of the nucleosides in X is a 2'- modified nucleoside; Y comprises 6-14 linked 2'-deoxyribonucleosides, wherein each cytidine in Y is optionally and independently a 5-methyl-cytidine; and Z comprises 3-5 linked nucleosides, wherein at least one of the nucleosides in Z is a 2'- modified nucleoside.

[00011] In some embodiments, the oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 165-167, wherein X comprises 5 linked nucleosides and each nucleoside in X is a 2'-MOE modified nucleoside; Y comprises 10 linked 2'-deoxyribonucleosides, wherein each cytidine in Y is optionally and independently a 5-methyl-cytidine; and Z comprises 5 linked nucleosides and each nucleoside in Z is a 2'-MOE modified nucleoside.

[00012] In some embodiments, the oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 165-167, wherein X comprises 5 linked nucleosides, wherein each nucleoside in X is a LNA nucleoside; Y comprises 10 linked 2'-deoxyribonucleosides, wherein each cytidine in Y is optionally and independently a 5-methyl-cytidine; and Z comprises 5 linked nucleosides, wherein each nucleoside in Z is a LNA nucleoside.

[00013] In some embodiments, the oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 171-173, wherein X comprises 3 linked nucleosides, wherein each nucleoside in X is a LNA nucleoside; Y comprises 14 linked 2'-deoxyribonucleosides, wherein each cytidine in Y is optionally and independently a 5-methyl-cytidine; and Z comprises 3 linked nucleosides, wherein each nucleoside in Z is a LNA nucleoside.

[00014] In some embodiments, the oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 168-170, and wherein each nucleoside of the oligonucleotide is a 2'-MOE modified nucleoside.

[00015] In some embodiments, the oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 168-170, and wherein each T in the oligonucleotide is a LNA nucleoside, and each C in the oligonucleotide is a 5-methyl-deoxycytidine.

[00016] In some embodiments, the oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 174-176, and wherein each C in the oligonucleotide is a LNA nucleoside and each T is a deoxythymidine.

[00017] In some embodiments, the oligonucleotide comprises one or more phosphorothioate internucleoside linkages. In some embodiments, the each internucleoside linkage in the oligonucleotide is a phosphorothioate internucleoside linkage.

[00018] In some embodiments, the oligonucleotide is selected from:

oC*oU*oU*oC*oU*dT*xC*dT*dT*xC*dT*dT*xC*dT*dT*oC*oU*oU*oC*oU (SEQ ID NO: 165)
oU*oU*oC*oU*oU*xC*dT*dT*xC*dT*dT*xC*dT*dT*xC*dT*oU*oU*oC*oU*oU (SEQ ID NO: 166)
oU*oC*oU*oU*oC*dT*dT*xC*dT*dT*xC*dT*dT*xC*dT*oU*oC*oU*oU*oC (SEQ ID NO: 167)
oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU (SEQ ID NO: 168)
oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU (SEQ ID NO: 169)
oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC (SEQ ID NO: 170)
+C*+U*+U*xC*dT*dT*xC*dT*dT*xC*dT*dT*xC*dT*dT*xC*dT*+U*+C*+U (SEQ ID NO: 171)
+U*+U*+C*dT*dT*xC*dT*dT*xC*dT*dT*xC*dT*dT*xC*dT*dT*+C*+U*+U (SEQ ID NO: 172)
+U*+C*+U*dT*xC*dT*dT*xC*dT*dT*xC*dT*dT*xC*dT*dT*xC*dT*+U*+U*+C (SEQ ID NO: 173)
+C*+U*+U*+C*+U*dT*xC*dT*dT*xC*dT*dT*xC*dT*dT*+C*+U*+U*+C*+U (SEQ ID NO: 165)
+U*+U*+C*+U*+U*xC*dT*dT*xC*dT*dT*xC*dT*dT*xC*dT*+U*+U*+C*+U*+U (SEQ ID NO: 166)
+U*+C*+U*+U*+C*dT*dT*xC*dT*dT*xC*dT*dT*xC*dT*+U*+C*+U*+U*+C (SEQ ID NO: 167)
xC*dT*+U*+U*xC*dT*+U*+U*xC*dT*+U*+U*xC*dT*+U*+U*xC*dT*+U*+U*xC*dT*+U (SEQ ID NO: 168)
+U*+U*xC*dT*+U*+U*xC*dT*+U*+U*xC*dT*+U*+U*xC*dT*+U*+U*xC*dT*+U*+U (SEQ ID NO: 169)
+U*xC*dT*+U*+U*xC*dT*+U*+U*xC*dT*+U*+U*xC*dT*+U*+U*xC*dT*+U*+U*xC (SEQ ID NO: 170)
+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT (SEQ ID NO: 174)
dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT (SEQ ID NO: 175)
dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C (SEQ ID NO: 176)

wherein “xdC” indicates a 5-methyl-deoxycytidine; “dN” indicates a 2’-deoxyribonucleoside; “+N” indicates a LNA nucleoside; “oN” indicates a 2’- MOE modified ribonucleoside; “oC” indicates a 5-methyl-2’-MOE-cytidine; “+C” indicates a 5-methyl-2’-4’-bicyclic-cytidine (2’-4’ methylene bridge); “oU” indicates a 5-methyl-2’-MOE-uridine; “+U” indicates a 5-methyl-2’-4’-bicyclic-uridine (2’-4’ methylene bridge); “*” indicates a phosphorothioate internucleoside linkage.

[00019] In some embodiments, the anti-TfR1 antibody comprises a heavy chain complementarity determining region 1 (CDR-H1), a heavy chain complementarity determining region 2 (CDR-H2), a heavy chain complementarity determining region 3 (CDR-H3), a light chain complementarity determining region 1 (CDR-L1), a light chain complementarity determining region 2 (CDR-L2), a light chain complementarity determining region 3 (CDR-L3) of any of the anti-TfR1 antibodies listed in Table 2.

[00020] In some embodiments, the anti-TfR1 antibody comprises a heavy chain variable region (VH) and a light chain variable region (VL) of any of the anti-TfR1 antibodies listed in Table 3. In some embodiments, the anti-TfR1 antibody is a Fab. In some embodiments, the Fab comprises a heavy chain and a light chain of any of the anti-TfR1 Fabs listed in Table 5.

[00021] In some embodiments, the muscle targeting agent and the oligonucleotide are covalently linked via a linker. In some embodiments, the linker comprises a valine-citrulline sequence.

[00022] Some aspects of the present disclosure provide methods of increasing FXN expression in a muscle cell, the method comprising contacting the muscle cell with an effective amount of the complex described herein for promoting internalization of the oligonucleotide to the muscle cell.

[00023] Some aspects of the present disclosure provide methods of treating Friedreich’s Ataxia (FA), the method comprising administering to a subject in need thereof an effective amount of the complex described herein, wherein the subject has a mutant FXN allele comprising disease-associated GAA repeats.

[00024] In some embodiments, administration of the complex results in an increase of FXN protein level.

[00025] Some aspects of the present disclosure provide oligonucleotide selected from:

oC*oU*oU*oC*oU*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*oC*oU*oU*oC*oU (SEQ ID NO: 165)

oU*oU*oC*oU*oU*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*oU*oU*oC*oU*oU (SEQ ID NO: 166)

oU*oC*oU*oU*oC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*oU*oC*oU*oU*oC (SEQ ID NO: 167)

wherein “xdC” indicates a 5-methyl-deoxycytidine; “dN” indicates a 2’-deoxyribonucleoside; “+N” indicates a LNA nucleoside; “oN” indicates a 2’- MOE modified ribonucleoside; “oC” indicates a 5-methyl-2’-MOE-cytidine; “+C” indicates a 5-methyl-2’-4’-bicyclic-cytidine (2’-4’ methylene bridge); “oU” indicates a 5-methyl-2’-MOE-uridine; “+U” indicates a 5-methyl-2’-4’-bicyclic-uridine (2’-4’ methylene bridge); “*” indicates a phosphorothioate internucleoside linkage.

[00026] Compositions comprising the oligonucleotide described herein in sodium salt form, are also provided.

BRIEF DESCRIPTION OF THE DRAWINGS

[00027] FIGs. 1A-1H show that conjugates having an anti-TfR1 Fab conjugated to a DMPK-targeting oligonucleotide reduced mouse DMPK expression in various muscle tissues in a mouse model that expresses human TfR1. The DMPK-targeting oligonucleotide was conjugated to anti-TfR1 Fab 3M12-VH4/VK3. FIG. 1A shows that the conjugate reduced mouse wild-type *Dmpk* in Tibialis Anterior by 79%. FIG. 1B shows that the conjugate reduced mouse wild-type *Dmpk* in gastrocnemius by 76%. FIG. 1C shows that the conjugate reduced mouse wild-type *Dmpk* in the heart by 70%. FIG. 1D shows that the conjugate reduced mouse wild-type *Dmpk* and in diaphragm by 88%. FIGs. 1E-1H show oligonucleotide distributions in Tibialis Anterior (FIG. 1E), gastrocnemius (FIG. 1F), heart (FIG. 1G), and diaphragm (FIG. 1H). All tissues showed increased level of the oligonucleotide compared to the vehicle control.

DETAILED DESCRIPTION

[00028] According to some aspects, the disclosure provides oligonucleotides designed to target FXN RNAs. In some embodiments, the disclosure provides oligonucleotides complementary with FXN RNA that are useful for increasing levels of functional FXN blocking FXN RNA containing expanded GAA repeats, *e.g.*, in a subject having or suspected of having Friedreich's ataxia. In some embodiments, the oligonucleotides are designed to direct RNase H mediated degradation of the FXN RNA containing expanded GAA repeats. In some embodiments, the oligonucleotides are designed to inhibit formation of an RNA loop (R-loop) by the FXN RNA containing expanded GAA repeats with chromosomal DNA. In some embodiments, the oligonucleotides are designed to have desirable bioavailability and/or serum-stability properties. In some embodiments, the oligonucleotides are designed to have desirable binding affinity properties. In some embodiments, the oligonucleotides are designed to have desirable toxicity profiles. In some embodiments, the oligonucleotides are designed to have low-complement activation and/or cytokine induction properties.

[00029] In some embodiments, oligonucleotides provided herein are conjugated to other molecules, *e.g.*, targeting agents, *e.g.*, muscle targeting agents. Accordingly, in some aspects, the disclosure provides complexes that target specific cell types for purposes of delivering the oligonucleotides to those cells. For example, in some embodiments, the disclosure provides complexes that target muscle cells for purposes of delivering oligonucleotides to muscle cells. In some embodiments, complexes provided herein are particularly useful for delivering molecular payloads that increase the expression or activity of functional FXN protein by reducing the level of FXN RNA containing an expanded disease-associated-repeat, *e.g.*, in a subject having or suspected of having Friedreich's ataxia. In some embodiments, complexes provided herein comprise muscle-targeting agents (*e.g.*, muscle targeting antibodies) that specifically bind to receptors on the surface of muscle cells for purposes of delivering molecular payloads to the muscle cells. In some embodiments, the complexes are taken up into the cells via a receptor mediated internalization, following which the molecular payload may be released to perform a function inside the cells. For example, complexes engineered to deliver oligonucleotides may release the oligonucleotides such that the oligonucleotides can block mutant FXN in the muscle cells. In some embodiments, the oligonucleotides are released by endosomal cleavage of covalent linkers connecting oligonucleotides and muscle-targeting agents of the complexes.

[00030] As one example, oligonucleotides may target an R-loop portion of FXN that has an expansion of GAA repeats in order to increase frataxin expression. In some embodiments,

inhibition of R-loop formation, *e.g.*, with a molecular payload capable of binding to the expanded GAA repeat, can allow for normal expression of the FXN gene and treatment of the disease. In some embodiments, complexes provided herein may comprise molecular payloads such as antisense oligonucleotides (ASO) that are capable of targeting a sequence at or near a disease-associated repeat GAA sequence of FXN. Further aspects of the disclosure, including a description of defined terms, are provided below.

I. Definitions

[00031] Administering: As used herein, the terms “administering” or “administration” means to provide a complex to a subject in a manner that is physiologically and/or (*e.g.*, and) pharmacologically useful (*e.g.*, to treat a condition in the subject).

[00032] Approximately: As used herein, the term “approximately” or “about,” as applied to one or more values of interest, refers to a value that is similar to a stated reference value. In certain embodiments, the term “approximately” or “about” refers to a range of values that fall within 15%, 14%, 13%, 12%, 11%, 10%, 9%, 8%, 7%, 6%, 5%, 4%, 3%, 2%, 1%, or less in either direction (greater than or less than) of the stated reference value unless otherwise stated or otherwise evident from the context (except where such number would exceed 100% of a possible value).

[00033] Antibody: As used herein, the term “antibody” refers to a polypeptide that includes at least one immunoglobulin variable domain or at least one antigenic determinant, *e.g.*, paratope that specifically binds to an antigen. In some embodiments, an antibody is a full-length antibody. In some embodiments, an antibody is a chimeric antibody. In some embodiments, an antibody is a humanized antibody. However, in some embodiments, an antibody is a Fab fragment, a Fab' fragment, a F(ab')₂ fragment, a Fv fragment or a scFv fragment. In some embodiments, an antibody is a nanobody derived from a camelid antibody or a nanobody derived from shark antibody. In some embodiments, an antibody is a diabody. In some embodiments, an antibody comprises a framework having a human germline sequence. In another embodiment, an antibody comprises a heavy chain constant domain selected from the group consisting of IgG, IgG1, IgG2, IgG2A, IgG2B, IgG2C, IgG3, IgG4, IgA1, IgA2, IgD, IgM, and IgE constant domains. In some embodiments, an antibody comprises a heavy (H) chain variable region (abbreviated herein as VH), and/or (*e.g.*, and) a light (L) chain variable region (abbreviated herein as VL). In some embodiments, an antibody comprises a constant domain, *e.g.*, an Fc region. An immunoglobulin constant domain refers to a heavy or light chain constant domain. Human IgG heavy chain and light chain constant domain amino acid sequences and their functional variations are known. With respect to the heavy chain, in some

embodiments, the heavy chain of an antibody described herein can be an alpha (α), delta (Δ), epsilon (ϵ), gamma (γ) or mu (μ) heavy chain. In some embodiments, the heavy chain of an antibody described herein can comprise a human alpha (α), delta (Δ), epsilon (ϵ), gamma (γ) or mu (μ) heavy chain. In a particular embodiment, an antibody described herein comprises a human gamma 1 CH1, CH2, and/or (e.g., and) CH3 domain. In some embodiments, the amino acid sequence of the VH domain comprises the amino acid sequence of a human gamma (γ) heavy chain constant region, such as any known in the art. Non-limiting examples of human constant region sequences have been described in the art, e.g., see U.S. Pat. No. 5,693,780 and Kabat E A et al., (1991) *supra*. In some embodiments, the VH domain comprises an amino acid sequence that is at least 70%, 75%, 80%, 85%, 90%, 95%, 98%, or at least 99% identical to any of the variable chain constant regions provided herein. In some embodiments, an antibody is modified, e.g., modified via glycosylation, phosphorylation, sumoylation, and/or (e.g., and) methylation. In some embodiments, an antibody is a glycosylated antibody, which is conjugated to one or more sugar or carbohydrate molecules. In some embodiments, the one or more sugar or carbohydrate molecule are conjugated to the antibody via N-glycosylation, O-glycosylation, C-glycosylation, glypiation (GPI anchor attachment), and/or (e.g., and) phosphoglycosylation. In some embodiments, the one or more sugar or carbohydrate molecule are monosaccharides, disaccharides, oligosaccharides, or glycans. In some embodiments, the one or more sugar or carbohydrate molecule is a branched oligosaccharide or a branched glycan. In some embodiments, the one or more sugar or carbohydrate molecule includes a mannose unit, a glucose unit, an N-acetylglucosamine unit, an N-acetylgalactosamine unit, a galactose unit, a fucose unit, or a phospholipid unit. In some embodiments, an antibody is a construct that comprises a polypeptide comprising one or more antigen binding fragments of the disclosure linked to a linker polypeptide or an immunoglobulin constant domain. Linker polypeptides comprise two or more amino acid residues joined by peptide bonds and are used to link one or more antigen binding portions. Examples of linker polypeptides have been reported (see e.g., Holliger, P., et al. (1993) *Proc. Natl. Acad. Sci. USA* 90:6444-6448; Poljak, R. J., et al. (1994) *Structure* 2:1121-1123). Still further, an antibody may be part of a larger immunoadhesion molecule, formed by covalent or noncovalent association of the antibody or antibody portion with one or more other proteins or peptides. Examples of such immunoadhesion molecules include use of the streptavidin core region to make a tetrameric scFv molecule (Kipriyanov, S. M., et al. (1995) *Human Antibodies and Hybridomas* 6:93-101) and use of a cysteine residue, a marker peptide and a C-terminal polyhistidine tag to make bivalent and biotinylated scFv molecules (Kipriyanov, S. M., et al. (1994) *Mol. Immunol.* 31:1047-1058).

[00034] **CDR:** As used herein, the term "CDR" refers to the complementarity determining region within antibody variable sequences. A typical antibody molecule comprises a heavy chain variable region (VH) and a light chain variable region (VL), which are usually involved in antigen binding. The VH and VL regions can be further subdivided into regions of hypervariability, also known as "complementarity determining regions" ("CDR"), interspersed with regions that are more conserved, which are known as "framework regions" ("FR"). Each VH and VL is typically composed of three CDRs and four FRs, arranged from amino-terminus to carboxy-terminus in the following order: FR1, CDR1, FR2, CDR2, FR3, CDR3, FR4. The extent of the framework region and CDRs can be precisely identified using methodology known in the art, for example, by the Kabat definition, the IMGT definition, the Chothia definition, the AbM definition, and/or (e.g., and) the contact definition, all of which are well known in the art. See, e.g., Kabat, E.A., et al. (1991) Sequences of Proteins of Immunological Interest, Fifth Edition, U.S. Department of Health and Human Services, NIH Publication No. 91-3242; IMGT®, the international ImMunoGeneTics information system® www.imgt.org, Lefranc, M.-P. et al., Nucleic Acids Res., 27:209-212 (1999); Ruiz, M. et al., Nucleic Acids Res., 28:219-221 (2000); Lefranc, M.-P., Nucleic Acids Res., 29:207-209 (2001); Lefranc, M.-P., Nucleic Acids Res., 31:307-310 (2003); Lefranc, M.-P. et al., In Silico Biol., 5, 0006 (2004) [Epub], 5:45-60 (2005); Lefranc, M.-P. et al., Nucleic Acids Res., 33:D593-597 (2005); Lefranc, M.-P. et al., Nucleic Acids Res., 37:D1006-1012 (2009); Lefranc, M.-P. et al., Nucleic Acids Res., 43:D413-422 (2015); Chothia et al., (1989) Nature 342:877; Chothia, C. et al. (1987) J. Mol. Biol. 196:901-917, Al-lazikani et al (1997) J. Molec. Biol. 273:927-948; and Almagro, J. Mol. Recognit. 17:132-143 (2004). See also hgmp.mrc.ac.uk and bioinf.org.uk/abs. As used herein, a CDR may refer to the CDR defined by any method known in the art. Two antibodies having the same CDR means that the two antibodies have the same amino acid sequence of that CDR as determined by the same method, for example, the IMGT definition.

[00035] There are three CDRs in each of the variable regions of the heavy chain and the light chain, which are designated CDR1, CDR2 and CDR3, for each of the variable regions. The term "CDR set" as used herein refers to a group of three CDRs that occur in a single variable region capable of binding the antigen. The exact boundaries of these CDRs have been defined differently according to different systems. The system described by Kabat (Kabat *et al.*, Sequences of Proteins of Immunological Interest (National Institutes of Health, Bethesda, Md. (1987) and (1991)) not only provides an unambiguous residue numbering system applicable to any variable region of an antibody, but also provides precise residue boundaries defining the three CDRs. These CDRs may be referred to as Kabat CDRs. Sub-portions of CDRs may be designated as L1, L2 and L3 or H1, H2 and H3 where the "L" and the "H" designates the light

chain and the heavy chains regions, respectively. These regions may be referred to as Chothia CDRs, which have boundaries that overlap with Kabat CDRs. Other boundaries defining CDRs overlapping with the Kabat CDRs have been described by Padlan (FASEB J. 9:133-139 (1995)) and MacCallum (J Mol Biol 262(5):732-45 (1996)). Still other CDR boundary definitions may not strictly follow one of the above systems, but will nonetheless overlap with the Kabat CDRs, although they may be shortened or lengthened in light of prediction or experimental findings that particular residues or groups of residues or even entire CDRs do not significantly impact antigen binding. The methods used herein may utilize CDRs defined according to any of these systems. Examples of CDR definition systems are provided in **Table 1**.

Table 1. CDR Definitions

	IMGT¹	Kabat²	Chothia³
CDR-H1	27-38	31-35	26-32
CDR-H2	56-65	50-65	53-55
CDR-H3	105-116/117	95-102	96-101
CDR-L1	27-38	24-34	26-32
CDR-L2	56-65	50-56	50-52
CDR-L3	105-116/117	89-97	91-96

¹ IMGT®, the international ImMunoGeneTics information system®, imgt.org, Lefranc, M.-P. et al., Nucleic Acids Res., 27:209-212 (1999)

² Kabat et al. (1991) Sequences of Proteins of Immunological Interest, Fifth Edition, U.S. Department of Health and Human Services, NIH Publication No. 91-3242

³ Chothia et al., J. Mol. Biol. 196:901-917 (1987))

[00036] CDR-grafted antibody: The term "CDR-grafted antibody" refers to antibodies which comprise heavy and light chain variable region sequences from one species but in which the sequences of one or more of the CDR regions of VH and/or (e.g., and) VL are replaced with CDR sequences of another species, such as antibodies having murine heavy and light chain variable regions in which one or more of the murine CDRs (e.g., CDR3) has been replaced with human CDR sequences.

[00037] Chimeric antibody: The term "chimeric antibody" refers to antibodies which comprise heavy and light chain variable region sequences from one species and constant region sequences from another species, such as antibodies having murine heavy and light chain variable regions linked to human constant regions.

[00038] Complementary: As used herein, the term "complementary" refers to the capacity for precise pairing between two nucleosides or two sets of nucleosides. In particular, complementary is a term that characterizes an extent of hydrogen bond pairing that brings about binding between two nucleosides or two sets of nucleosides. For example, if a base at one position of an oligonucleotide is capable of hydrogen bonding with a base at the corresponding position of a target nucleic acid (e.g., an mRNA), then the bases are considered to be

complementary to each other at that position. Base pairings may include both canonical Watson-Crick base pairing and non-Watson-Crick base pairing (e.g., Wobble base pairing and Hoogsteen base pairing). For example, in some embodiments, for complementary base pairings, adenosine-type bases (A) are complementary to thymidine-type bases (T) or uracil-type bases (U), that cytosine-type bases (C) are complementary to guanosine-type bases (G), and that universal bases such as 3-nitropyrrole or 5-nitroindole can hybridize to and are considered complementary to any A, C, U, or T. Inosine (I) has also been considered in the art to be a universal base and is considered complementary to any A, C, U or T.

[00039] Conservative amino acid substitution: As used herein, a “conservative amino acid substitution” refers to an amino acid substitution that does not alter the relative charge or size characteristics of the protein in which the amino acid substitution is made. Variants can be prepared according to methods for altering polypeptide sequence known to one of ordinary skill in the art such as are found in references which compile such methods, e.g., *Molecular Cloning: A Laboratory Manual*, J. Sambrook, et al., eds., Fourth Edition, Cold Spring Harbor Laboratory Press, Cold Spring Harbor, New York, 2012, or *Current Protocols in Molecular Biology*, F.M. Ausubel, et al., eds., John Wiley & Sons, Inc., New York. Conservative substitutions of amino acids include substitutions made amongst amino acids within the following groups: (a) M, I, L, V; (b) F, Y, W; (c) K, R, H; (d) A, G; (e) S, T; (f) Q, N; and (g) E, D.

[00040] Covalently linked: As used herein, the term “covalently linked” refers to a characteristic of two or more molecules being linked together via at least one covalent bond. In some embodiments, two molecules can be covalently linked together by a single bond, e.g., a disulfide bond or disulfide bridge, that serves as a linker between the molecules. However, in some embodiments, two or more molecules can be covalently linked together via a molecule that serves as a linker that joins the two or more molecules together through multiple covalent bonds. In some embodiments, a linker may be a cleavable linker. However, in some embodiments, a linker may be a non-cleavable linker.

[00041] Cross-reactive: As used herein and in the context of a targeting agent (e.g., antibody), the term “cross-reactive,” refers to a property of the agent being capable of specifically binding to more than one antigen of a similar type or class (e.g., antigens of multiple homologs, paralogs, or orthologs) with similar affinity or avidity. For example, in some embodiments, an antibody that is cross-reactive against human and non-human primate antigens of a similar type or class (e.g., a human transferrin receptor and non-human primate transferrin receptor) is capable of binding to the human antigen and non-human primate antigens with a similar affinity or avidity. In some embodiments, an antibody is cross-reactive against a human antigen and a rodent antigen of a similar type or class. In some embodiments, an antibody is

cross-reactive against a rodent antigen and a non-human primate antigen of a similar type or class. In some embodiments, an antibody is cross-reactive against a human antigen, a non-human primate antigen, and a rodent antigen of a similar type or class.

[00042] Disease-associated-repeat: As used herein, the term “disease-associated-repeat” refers to a repeated nucleotide sequence at a genomic location for which the number of units of the repeated nucleotide sequence is correlated with and/or (e.g., and) directly or indirectly contributes to, or causes, genetic disease. Each repeating unit of a disease associated repeat may be 2, 3, 4, 5 or more nucleotides in length. For example, in some embodiments, a disease associated repeat is a dinucleotide repeat. In some embodiments, a disease associated repeat is a trinucleotide repeat. In some embodiments, a disease associated repeat is a tetranucleotide repeat. In some embodiments, a disease associated repeat is a pentanucleotide repeat. In some embodiments, the disease-associated-repeat comprises GAA repeats or a nucleotide complement of any thereof. In some embodiments, a disease-associated-repeat is in a non-coding portion of a gene. However, in some embodiments, a disease-associated-repeat is in a coding region of a gene. In some embodiments, a disease-associated-repeat is expanded from a normal state to a length that directly or indirectly contributes to, or causes, genetic disease. In some embodiments, a disease-associated-repeat is in RNA (e.g., an RNA transcript). In some embodiments, a disease-associated-repeat is in DNA (e.g., a chromosome, a plasmid). In some embodiments, a disease-associated-repeat is expanded in a chromosome of a germline cell. In some embodiments, a disease-associated-repeat is expanded in a chromosome of a somatic cell. In some embodiments, a disease-associated-repeat is expanded to a number of repeating units that is associated with congenital onset of disease. In some embodiments, a disease-associated-repeat is expanded to a number of repeating units that is associated with childhood onset of disease. In some embodiments, a disease-associated-repeat is expanded to a number of repeating units that is associated with adult onset of disease.

[00043] Framework: As used herein, the term "framework" or "framework sequence" refers to the remaining sequences of a variable region minus the CDRs. Because the exact definition of a CDR sequence can be determined by different systems, the meaning of a framework sequence is subject to correspondingly different interpretations. The six CDRs (CDR-L1, CDR-L2, and CDR-L3 of light chain and CDR-H1, CDR-H2, and CDR-H3 of heavy chain) also divide the framework regions on the light chain and the heavy chain into four sub-regions (FR1, FR2, FR3 and FR4) on each chain, in which CDR1 is positioned between FR1 and FR2, CDR2 between FR2 and FR3, and CDR3 between FR3 and FR4. Without specifying the particular sub-regions as FR1, FR2, FR3 or FR4, a framework region, as referred by others, represents the combined FRs within the variable region of a single, naturally occurring

immunoglobulin chain. As used herein, a FR represents one of the four sub-regions, and FRs represents two or more of the four sub-regions constituting a framework region. Human heavy chain and light chain acceptor sequences are known in the art. In one embodiment, the acceptor sequences known in the art may be used in the antibodies disclosed herein.

[00044] Friedreich's ataxia: As used herein, the term "Friedreich's ataxia" refers to an autosomal recessive genetic disease caused by mutations in the FXN gene and is characterized by progressive damage of muscle tissues and the nervous system. Friedreich's ataxia is associated with an expansion of a GAA trinucleotide repeat in the FXN gene that leads to a decrease in the expression of FXN. The expanded GAA trinucleotide repeat, located within the first intron, forms a R-loop which can interfere with normal transcriptional processes to reduce FXN gene expression. FXN alleles in healthy individuals contain <36 GAA repeats, whereas in FRDA patients GAA expansions ranging from 70 to 1700 GAA repeats lead to FXN mRNA deficiency and subsequent reduced levels of frataxin, a nuclear-encoded mitochondrial protein essential for life (see, e.g., Silva et al., "Expanded GAA repeats impair FXN gene expression and reposition the FXN locus to the nuclear lamina in single cells." *Hum. Molec. Genet.*, 2015, Vol. 24, No. 12 3457–3471). Friedreich's ataxia, the genetic basis for the disease, and related symptoms are described in the art (see, e.g., Montermini, L. et al. "The Friedreich's ataxia GAA triplet repeat: premutation and normal alleles." *Hum. Molec. Genet.*, 1997, 6: 1261-1266.; Filla, A. et al. "The relationship between trinucleotide (GAA) repeat length and clinical features in Friedreich's ataxia." *Am. J. Hum. Genet.* 1996, 59: 554-560.; Pandolfo, M. Friedreich's ataxia: the clinical picture. *J. Neurol.* 2009, 256, 3–8.) Friedreich's ataxia is associated with Online Mendelian Inheritance in Man (OMIM) Entry # 229300.

[00045] FXN: As used herein, the term "FXN" refers to a gene that encodes frataxin, a protein implicated in iron homeostasis. In some embodiments, FXN may be a human (Gene ID: 2395), non-human primate (e.g., Gene ID: 737660), or rodent gene (e.g., Gene ID: 14297, Gene ID: 499335). In humans, a GAA repeat expansion in the first intron of FXN is associated with Friedreich's ataxia. In addition, multiple human transcript variants (e.g., as annotated under GenBank RefSeq Accession Numbers: NM_000144.4 and NM_181425.2) have been characterized that encode different protein isoforms.

[00046] FXN allele: As used herein, the term "FXN allele" refers to any one of alternative forms (e.g., wild-type or mutant forms) of a FXN gene. In some embodiments, a FXN allele may encode for wild-type frataxin that retains its normal and typical functions. In some embodiments, a FXN allele may comprise one or more disease-associated-repeat expansions. In some embodiments, normal subjects have two FXN alleles comprising less than 36 GAA trinucleotide repeat units. In some embodiments, normal subjects have two FXN

alleles comprising in the range of 8 to 33 GAA trinucleotide repeat units. In some embodiments, the number of GAA repeat units in an FXN allele of subjects having Friedreich's ataxia is in the range of approximately 70 to approximately 1700. In some embodiments, the number of GAA repeat units in an FXN allele of subjects having Friedreich's ataxia is in the range of approximately 90 to approximately 1300 with higher numbers of repeats leading to an increased severity of disease. In some embodiments, mildly affected Friedreich's ataxia subjects have at least one FXN allele having in the range of 90 to 150 repeat units. In some embodiments, subjects with classic Friedreich's ataxia have at least one FXN allele having in the range of 90 to 1,000 or more repeat units.

[00047] Human antibody: The term "human antibody", as used herein, is intended to include antibodies having variable and constant regions derived from human germline immunoglobulin sequences. The human antibodies of the disclosure may include amino acid residues not encoded by human germline immunoglobulin sequences (*e.g.*, mutations introduced by random or site-specific mutagenesis *in vitro* or by somatic mutation *in vivo*), for example in the CDRs and in particular CDR3. However, the term "human antibody", as used herein, is not intended to include antibodies in which CDR sequences derived from the germline of another mammalian species, such as a mouse, have been grafted onto human framework sequences.

[00048] Humanized antibody: The term "humanized antibody" refers to antibodies which comprise heavy and light chain variable region sequences from a non-human species (*e.g.*, a mouse) but in which at least a portion of the VH and/or (*e.g.*, and) VL sequence has been altered to be more "human-like", *i.e.*, more similar to human germline variable sequences. One type of humanized antibody is a CDR-grafted antibody, in which human CDR sequences are introduced into non-human VH and VL sequences to replace the corresponding non-human CDR sequences. In one embodiment, humanized anti-transferrin receptor (TfR1) antibodies and antigen binding portions are provided. Such antibodies may be generated by obtaining murine anti-transferrin receptor (TfR1) monoclonal antibodies using traditional hybridoma technology followed by humanization using *in vitro* genetic engineering, such as those disclosed in Kasaian et al PCT publication No. WO 2005/123126 A2.

[00049] Internalizing cell surface receptor: As used herein, the term, "internalizing cell surface receptor" refers to a cell surface receptor that is internalized by cells, *e.g.*, upon external stimulation, *e.g.*, ligand binding to the receptor. In some embodiments, an internalizing cell surface receptor is internalized by endocytosis. In some embodiments, an internalizing cell surface receptor is internalized by clathrin-mediated endocytosis. However, in some embodiments, an internalizing cell surface receptor is internalized by a clathrin-independent pathway, such as, for example, phagocytosis, macropinocytosis, caveolae- and raft-mediated

uptake or constitutive clathrin-independent endocytosis. In some embodiments, the internalizing cell surface receptor comprises an intracellular domain, a transmembrane domain, and/or (e.g., and) an extracellular domain, which may optionally further comprise a ligand-binding domain. In some embodiments, a cell surface receptor becomes internalized by a cell after ligand binding. In some embodiments, a ligand may be a muscle-targeting agent or a muscle-targeting antibody. In some embodiments, an internalizing cell surface receptor is a transferrin receptor.

[00050] Isolated antibody: An "isolated antibody", as used herein, is intended to refer to an antibody that is substantially free of other antibodies having different antigenic specificities (e.g., an isolated antibody that specifically binds transferrin receptor is substantially free of antibodies that specifically bind antigens other than transferrin receptor). An isolated antibody that specifically binds transferrin receptor complex may, however, have cross-reactivity to other antigens, such as transferrin receptor molecules from other species. Moreover, an isolated antibody may be substantially free of other cellular material and/or (e.g., and) chemicals.

[00051] Kabat numbering: The terms "Kabat numbering", "Kabat definitions and "Kabat labeling" are used interchangeably herein. These terms, which are recognized in the art, refer to a system of numbering amino acid residues which are more variable (i.e. hypervariable) than other amino acid residues in the heavy and light chain variable regions of an antibody, or an antigen binding portion thereof (Kabat et al. (1971) Ann. NY Acad. Sci. 190:382-391 and, Kabat, E. A., *et al.* (1991) Sequences of Proteins of Immunological Interest, Fifth Edition, U.S. Department of Health and Human Services, NIH Publication No. 91-3242). For the heavy chain variable region, the hypervariable region ranges from amino acid positions 31 to 35 for CDR1, amino acid positions 50 to 65 for CDR2, and amino acid positions 95 to 102 for CDR3. For the light chain variable region, the hypervariable region ranges from amino acid positions 24 to 34 for CDR1, amino acid positions 50 to 56 for CDR2, and amino acid positions 89 to 97 for CDR3.

[00052] Molecular payload: As used herein, the term "molecular payload" refers to a molecule or species that functions to modulate a biological outcome. In some embodiments, a molecular payload is linked to, or otherwise associated with a muscle-targeting agent. In some embodiments, a molecular payload is covalently linked to a muscle-targeting agent. In some embodiments, the molecular payload is a small molecule, a protein, a peptide, a nucleic acid, or an oligonucleotide. In some embodiments, the molecular payload functions to modulate the transcription of a DNA sequence, to modulate the expression of a protein, or to modulate the activity of a protein. In some embodiments, the molecular payload is an oligonucleotide that comprises a strand having a region of complementarity to a target gene.

[00053] Muscle-targeting agent: As used herein, the term, “muscle-targeting agent,” refers to a molecule that specifically binds to an antigen expressed on muscle cells. The antigen in or on muscle cells may be a membrane protein, for example an integral membrane protein or a peripheral membrane protein. Typically, a muscle-targeting agent specifically binds to an antigen on muscle cells that facilitates internalization of the muscle-targeting agent (and any associated molecular payload) into the muscle cells. In some embodiments, a muscle-targeting agent specifically binds to an internalizing, cell surface receptor on muscles and is capable of being internalized into muscle cells through receptor mediated internalization. In some embodiments, the muscle-targeting agent is a small molecule, a protein, a peptide, a nucleic acid (e.g., an aptamer), or an antibody. In some embodiments, the muscle-targeting agent is linked to a molecular payload.

[00054] Muscle-targeting antibody: As used herein, the term, “muscle-targeting antibody,” refers to a muscle-targeting agent that is an antibody that specifically binds to an antigen found in or on muscle cells. In some embodiments, a muscle-targeting antibody specifically binds to an antigen on muscle cells that facilitates internalization of the muscle-targeting antibody (and any associated molecular payment) into the muscle cells. In some embodiments, the muscle-targeting antibody specifically binds to an internalizing, cell surface receptor present on muscle cells. In some embodiments, the muscle-targeting antibody is an antibody that specifically binds to a transferrin receptor.

[00055] Oligonucleotide: As used herein, the term “oligonucleotide” refers to an oligomeric nucleic acid compound of up to 200 nucleotides in length. Examples of oligonucleotides include, but are not limited to, RNAi oligonucleotides (e.g., siRNAs, shRNAs), microRNAs, gapmers, mixmers, phosphorodiamidate morpholinos, peptide nucleic acids, aptamers, guide nucleic acids (e.g., Cas9 guide RNAs), etc. Oligonucleotides may be single-stranded or double-stranded. In some embodiments, an oligonucleotide may comprise one or more modified nucleosides (e.g., 2'-O-methyl sugar modifications, purine or pyrimidine modifications). In some embodiments, an oligonucleotide may comprise one or more modified internucleoside linkages. In some embodiments, an oligonucleotide may comprise one or more phosphorothioate linkages, which may be in the Rp or Sp stereochemical conformation.

[00056] Recombinant antibody: The term "recombinant human antibody", as used herein, is intended to include all human antibodies that are prepared, expressed, created or isolated by recombinant means, such as antibodies expressed using a recombinant expression vector transfected into a host cell (described in more details in this disclosure), antibodies isolated from a recombinant, combinatorial human antibody library (Hoogenboom H. R., (1997) TIB Tech. 15:62-70; Azzazy H., and Highsmith W. E., (2002) Clin. Biochem. 35:425-445;

Gavilondo J. V., and Larrick J. W. (2002) *BioTechniques* 29:128-145; Hoogenboom H., and Chames P. (2000) *Immunology Today* 21:371-378), antibodies isolated from an animal (e.g., a mouse) that is transgenic for human immunoglobulin genes (see e.g., Taylor, L. D., et al. (1992) *Nucl. Acids Res.* 20:6287-6295; Kellermann S-A., and Green L. L. (2002) *Current Opinion in Biotechnology* 13:593-597; Little M. et al (2000) *Immunology Today* 21:364-370) or antibodies prepared, expressed, created or isolated by any other means that involves splicing of human immunoglobulin gene sequences to other DNA sequences. Such recombinant human antibodies have variable and constant regions derived from human germline immunoglobulin sequences. In certain embodiments, however, such recombinant human antibodies are subjected to *in vitro* mutagenesis (or, when an animal transgenic for human Ig sequences is used, *in vivo* somatic mutagenesis) and thus the amino acid sequences of the VH and VL regions of the recombinant antibodies are sequences that, while derived from and related to human germline VH and VL sequences, may not naturally exist within the human antibody germline repertoire *in vivo*. One embodiment of the disclosure provides fully human antibodies capable of binding human transferrin receptor which can be generated using techniques well known in the art, such as, but not limited to, using human Ig phage libraries such as those disclosed in Jermutus et al., PCT publication No. WO 2005/007699 A2.

[00057] Region of complementarity: As used herein, the term “region of complementarity” refers to a nucleotide sequence, e.g., of an oligonucleotide, that is sufficiently complementary to a cognate nucleotide sequence, e.g., of a target nucleic acid, such that the two nucleotide sequences are capable of annealing to one another under physiological conditions (e.g., in a cell). In some embodiments, a region of complementarity is fully complementary to a cognate nucleotide sequence of target nucleic acid. However, in some embodiments, a region of complementarity is partially complementary to a cognate nucleotide sequence of target nucleic acid (e.g., at least 80%, 90%, 95% or 99% complementarity). In some embodiments, a region of complementarity contains 1, 2, 3, or 4 mismatches compared with a cognate nucleotide sequence of a target nucleic acid.

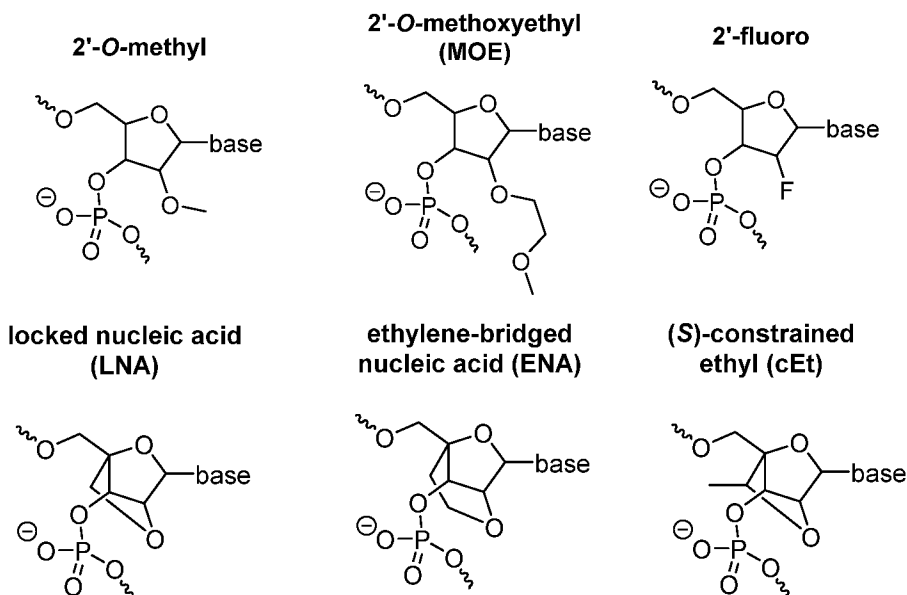
[00058] Specifically binds: As used herein, the term “specifically binds” refers to the ability of a molecule to bind to a binding partner with a degree of affinity or avidity that enables the molecule to be used to distinguish the binding partner from an appropriate control in a binding assay or other binding context. With respect to an antibody, the term, “specifically binds”, refers to the ability of the antibody to bind to a specific antigen with a degree of affinity or avidity, compared with an appropriate reference antigen or antigens, that enables the antibody to be used to distinguish the specific antigen from others, e.g., to an extent that permits preferential targeting to certain cells, e.g., muscle cells, through binding to the antigen, as

described herein. In some embodiments, an antibody specifically binds to a target if the antibody has a K_D for binding the target of at least about 10^{-4} M, 10^{-5} M, 10^{-6} M, 10^{-7} M, 10^{-8} M, 10^{-9} M, 10^{-10} M, 10^{-11} M, 10^{-12} M, 10^{-13} M, or less. In some embodiments, an antibody specifically binds to the transferrin receptor, e.g., an epitope of the apical domain of transferrin receptor.

[00059] Subject: As used herein, the term “subject” refers to a mammal. In some embodiments, a subject is non-human primate, or rodent. In some embodiments, a subject is a human. In some embodiments, a subject is a patient, e.g., a human patient that has or is suspected of having a disease. In some embodiments, the subject is a human patient who has or is suspected of having a disease resulting from a disease-associated-repeat expansion, e.g., in a FXN allele.

[00060] Transferrin receptor: As used herein, the term, “transferrin receptor” (also known as TFRC, CD71, p90, TFR, or TFR1) refers to an internalizing cell surface receptor that binds transferrin to facilitate iron uptake by endocytosis. In some embodiments, a transferrin receptor may be of human (NCBI Gene ID 7037), non-human primate (e.g., NCBI Gene ID 711568 or NCBI Gene ID 102136007), or rodent (e.g., NCBI Gene ID 22042) origin. In addition, multiple human transcript variants have been characterized that encoded different isoforms of the receptor (e.g., as annotated under GenBank RefSeq Accession Numbers: NP_001121620.1, NP_003225.2, NP_001300894.1, and NP_001300895.1).

[00061] 2'-modified nucleoside: As used herein, the terms “2'-modified nucleoside” and “2'-modified ribonucleoside” are used interchangeably and refer to a nucleoside having a sugar moiety modified at the 2' position. In some embodiments, the 2'-modified nucleoside is a 2'-4' bicyclic nucleoside, where the 2' and 4' positions of the sugar are bridged (e.g., via a methylene, an ethylene, or a (S)-constrained ethyl bridge). In some embodiments, the 2'-modified nucleoside is a non-bicyclic 2'-modified nucleoside, e.g., where the 2' position of the sugar moiety is substituted. Non-limiting examples of 2'-modified nucleosides include: 2'-deoxy, 2'-fluoro (2'-F), 2'-O-methyl (2'-O-Me), 2'-O-methoxyethyl (2'-MOE), 2'-O-aminopropyl (2'-O-AP), 2'-O-dimethylaminoethyl (2'-O-DMAOE), 2'-O-dimethylaminopropyl (2'-O-DMAP), 2'-O-dimethylaminoethoxyethyl (2'-O-DMAEOE), 2'-O-N-methylacetamido (2'-O-NMA), locked nucleic acid (LNA, methylene-bridged nucleic acid), ethylene-bridged nucleic acid (ENA), and (S)-constrained ethyl-bridged nucleic acid (cEt). In some embodiments, the 2'-modified nucleosides described herein are high-affinity modified nucleosides and oligonucleotides comprising the 2'-modified nucleosides have increased affinity to a target sequence, relative to an unmodified oligonucleotide. Examples of structures of 2'-modified nucleosides are provided below:



These examples are shown with phosphate groups, but any internucleoside linkages are contemplated between 2'-modified nucleosides.

II. Complexes

[00062] Further provided herein are complexes that comprise a targeting agent, e.g., an antibody, covalently linked to a molecular payload. In some embodiments, a complex comprises a muscle-targeting antibody covalently linked to an oligonucleotide. A complex may comprise an antibody that specifically binds a single antigenic site or that binds to at least two antigenic sites that may exist on the same or different antigens.

[00063] A complex may be used to modulate the activity or function of at least one gene, protein, and/or (e.g., and) nucleic acid. In some embodiments, the molecular payload present with a complex is responsible for the modulation of a gene, protein, and/or (e.g., and) nucleic acids. A molecular payload may be a small molecule, protein, nucleic acid, oligonucleotide, or any molecular entity capable of modulating the activity or function of a gene, protein, and/or (e.g., and) nucleic acid in a cell. In some embodiments, a molecular payload is an oligonucleotide that targets a disease-associated repeat in muscle cells.

[00064] In some embodiments, a complex comprises a muscle-targeting agent, e.g., an anti-transferrin receptor 1 (TfR1) antibody, covalently linked to a molecular payload, e.g., an antisense oligonucleotide that targets a disease-associated repeat, e.g., FXN allele.

A. Muscle-Targeting Agents

[00065] Some aspects of the disclosure provide muscle-targeting agents, e.g., for delivering a molecular payload to a muscle cell. In some embodiments, such muscle-targeting agents are capable of binding to a muscle cell, e.g., via specifically binding to an antigen on the

muscle cell, and delivering an associated molecular payload to the muscle cell. In some embodiments, the molecular payload is bound (*e.g.*, covalently bound) to the muscle targeting agent and is internalized into the muscle cell upon binding of the muscle targeting agent to an antigen on the muscle cell, *e.g.*, via endocytosis. It should be appreciated that various types of muscle-targeting agents may be used in accordance with the disclosure. It should be appreciated that various types of muscle-targeting agents may be used in accordance with the disclosure, and that any muscle targets (*e.g.*, muscle surface proteins) can be targeted by any type of muscle target agents described herein. For example, the muscle-targeting agent may comprise, or consist of, a small molecule, a nucleic acid (*e.g.*, DNA or RNA), a peptide (*e.g.*, an antibody), a lipid (*e.g.*, a microvesicle), or a sugar moiety (*e.g.*, a polysaccharide). Exemplary muscle-targeting agents are described in further detail herein, however, it should be appreciated that the exemplary muscle-targeting agents provided herein are not meant to be limiting.

[00066] Some aspects of the disclosure provide muscle-targeting agents that specifically bind to an antigen on muscle, such as skeletal muscle, smooth muscle, or cardiac muscle. In some embodiments, any of the muscle-targeting agents provided herein bind to (*e.g.*, specifically bind to) an antigen on a skeletal muscle cell, a smooth muscle cell, and/or (*e.g.*, and) a cardiac muscle cell.

[00067] By interacting with muscle-specific cell surface recognition elements (*e.g.*, cell membrane proteins), both tissue localization and selective uptake into muscle cells can be achieved. In some embodiments, molecules that are substrates for muscle uptake transporters are useful for delivering a molecular payload into muscle tissue. Binding to muscle surface recognition elements followed by endocytosis can allow even large molecules such as antibodies to enter muscle cells. As another example molecular payloads conjugated to transferrin or anti-transferrin receptor 1 (TfR1) antibodies can be taken up by muscle cells via binding to transferrin receptor, which may then be endocytosed, *e.g.*, via clathrin-mediated endocytosis.

[00068] The use of muscle-targeting agents may be useful for concentrating a molecular payload (*e.g.*, oligonucleotide) in muscle while reducing toxicity associated with effects in other tissues. In some embodiments, the muscle-targeting agent concentrates a bound molecular payload in muscle cells as compared to another cell type within a subject. In some embodiments, the muscle-targeting agent concentrates a bound molecular payload in muscle cells (*e.g.*, skeletal, smooth, or cardiac muscle cells) in an amount that is at least 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 15, 20, 30, 40, 50, 60, 70, 80, 90, or 100 times greater than an amount in non-muscle cells (*e.g.*, liver, neuronal, blood, or fat cells). In some embodiments, a toxicity of the molecular payload in a subject is reduced by at least 1%, 2%, 3%, 4%, 5%, 10%, 15%, 20%, 25%, 30%,

35%, 40%, 45%, 50%, 55%, 60%, 65%, 70%, 75%, 80%, 90%, or 95% when it is delivered to the subject when bound to the muscle-targeting agent.

[00069] In some embodiments, to achieve muscle selectivity, a muscle recognition element (*e.g.*, a muscle cell antigen) may be required. As one example, a muscle-targeting agent may be a small molecule that is a substrate for a muscle-specific uptake transporter. As another example, a muscle-targeting agent may be an antibody that enters a muscle cell via transporter-mediated endocytosis. As another example, a muscle targeting agent may be a ligand that binds to cell surface receptor on a muscle cell. It should be appreciated that while transporter-based approaches provide a direct path for cellular entry, receptor-based targeting may involve stimulated endocytosis to reach the desired site of action.

i. Muscle-Targeting Antibodies

[00070] In some embodiments, the muscle-targeting agent is an antibody. Generally, the high specificity of antibodies for their target antigen provides the potential for selectively targeting muscle cells (*e.g.*, skeletal, smooth, and/or (*e.g.*, and) cardiac muscle cells). This specificity may also limit off-target toxicity. Examples of antibodies that are capable of targeting a surface antigen of muscle cells have been reported and are within the scope of the disclosure. For example, antibodies that target the surface of muscle cells are described in Arahata K., et al. “Immunostaining of skeletal and cardiac muscle surface membrane with antibody against Duchenne muscular dystrophy peptide” *Nature* 1988; 333: 861-3; Song K.S., et al. “Expression of caveolin-3 in skeletal, cardiac, and smooth muscle cells. Caveolin-3 is a component of the sarcolemma and co-fractionates with dystrophin and dystrophin-associated glycoproteins” *J Biol Chem* 1996; 271: 15160-5; and Weisbart R.H. et al., “Cell type specific targeted intracellular delivery into muscle of a monoclonal antibody that binds myosin IIB” *Mol Immunol.* 2003 Mar, 39(13):78309; the entire contents of each of which are incorporated herein by reference.

a. Anti-Transferrin Receptor 1 (TfR1) Antibodies

[00071] Some aspects of the disclosure are based on the recognition that agents binding to transferrin receptor, *e.g.*, anti-transferrin-receptor antibodies, are capable of targeting muscle cell. Transferrin receptors are internalizing cell surface receptors that transport transferrin across the cellular membrane and participate in the regulation and homeostasis of intracellular iron levels. Some aspects of the disclosure provide transferrin receptor binding proteins, which are capable of binding to transferrin receptor. Accordingly, aspects of the disclosure provide binding proteins (*e.g.*, antibodies) that bind to transferrin receptor. In some embodiments, binding proteins that bind to transferrin receptor are internalized, along with any bound

molecular payload, into a muscle cell. As used herein, an antibody that binds to a transferrin receptor may be referred to interchangeably as a transferrin receptor antibody, an anti-transferrin receptor antibody, or an anti-TfR1 antibody. Antibodies that bind, e.g., specifically bind, to a transferrin receptor may be internalized into the cell, e.g., through receptor-mediated endocytosis, upon binding to a transferrin receptor.

[00072] It should be appreciated that anti-TfR1 antibodies may be produced, synthesized, and/or (e.g., and) derivatized using several known methodologies, e.g., library design using phage display. Exemplary methodologies have been characterized in the art and are incorporated by reference (Díez, P. et al. “High-throughput phage-display screening in array format”, *Enzyme and Microb Technol*, 2015, 79, 34-41.; Hammers C. M. and Stanley, J.R., “Antibody Phage Display: Technique and Applications” *J Invest Dermatol*. 2014, 134:2.; Engleman, Edgar (Ed.) “Human Hybridomas and Monoclonal Antibodies.” 1985, Springer.). In other embodiments, an anti-TfR1 antibody has been previously characterized or disclosed. Antibodies that specifically bind to transferrin receptor are known in the art (see, e.g., US Patent. No. 4,364,934, filed 12/4/1979, “Monoclonal antibody to a human early thymocyte antigen and methods for preparing same”; US Patent No. 8,409,573, filed 6/14/2006, “Anti-CD71 monoclonal antibodies and uses thereof for treating malignant tumor cells”; US Patent No. 9,708,406, filed 5/20/2014, “Anti-transferrin receptor antibodies and methods of use”; US 9,611,323, filed 12/19/2014, “Low affinity blood brain barrier receptor antibodies and uses therefor”; WO 2015/098989, filed 12/24/2014, “Novel anti-transferrin receptor antibody that passes through blood-brain barrier”; Schneider C. et al. “Structural features of the cell surface receptor for transferrin that is recognized by the monoclonal antibody OKT9.” *J Biol Chem*. 1982, 257:14, 8516-8522.; Lee et al. “Targeting Rat Anti-Mouse Transferrin Receptor Monoclonal Antibodies through Blood-Brain Barrier in Mouse” 2000, *J Pharmacol. Exp. Ther.*, 292: 1048-1052.).

[00073] In some embodiments, the anti-TfR1 antibody described herein binds to transferrin receptor with high specificity and affinity. In some embodiments, the anti-TfR1 antibody described herein specifically binds to any extracellular epitope of a transferrin receptor or an epitope that becomes exposed to an antibody. In some embodiments, anti-TfR1 antibodies provided herein bind specifically to transferrin receptor from human, non-human primates, mouse, rat, *etc.* In some embodiments, anti-TfR1 antibodies provided herein bind to human transferrin receptor. In some embodiments, the anti-TfR1 antibody described herein binds to an amino acid segment of a human or non-human primate transferrin receptor, as provided in SEQ ID NOs: 105-108. In some embodiments, the anti-TfR1 antibody described herein binds to an

amino acid segment corresponding to amino acids 90-96 of a human transferrin receptor as set forth in SEQ ID NO: 105, which is not in the apical domain of the transferrin receptor.

[00074] An example human transferrin receptor amino acid sequence, corresponding to NCBI sequence NP_003225.2 (transferrin receptor protein 1 isoform 1, *Homo sapiens*) is as follows:

MMDQARSASFNLFGGEPLSYTRFSLARQVDGDN SHVEMKLA VDEEENADNNTKANVT
KPKRCSGSICYGTIAVIVFFLIGFMIGYLG YCKGVEPKTECERLAGTESPVREEPGEDFPA
ARRLYWDDLKRKLSEKLDSTDFTGTIKLLNENSYVPREAGSQKDENLALYVENQFREF
KLSKVWRDQH FVKIQVKDSAQNSVIIVDKNGRLVYLVENPGGYVAYS KAATVTGKL V
HANFGTKKDFEDLYTPVNGSIVIVRAGKITFAEKVANAESLNAIGVLIYMDQTKFPIVNA
ELSFFGHAHLGTGDPYTPGFPSFNHTQFP PSRSSGLPNIPVQTISR AAAEKLFGNMEGDCP
SDWKTDSTCRMVTSESKNVKLT VSNVLKEIKILNIFGVIKGFVEPDHYVVVGAQRDAW
GPGAAGSGVGTALLLKL AQMFSDMV LKDG FQPSRSIIFASWSAGDFG SVGATEWLEGY
LSSLHLKAFTYINLDKAVLGTSNFKVSASPLLYTLIEKTMQNVKHPVTGQFLYQDSNWA
SKVEKLTLDNAAFPFLAYSGIPAVSFCFCEDTDYPYLGT TMDTYKELIERIPELNKVARA
AAEVAGQFVIKLTHDVELNLDYERYNSQLLSFVRDLNQYRADIKEMGLSLQWLYSARG
DFFRATSRLTTDFGNAEKTDRFVMKKLNDRVMRVEYHFLSPYVSPKESPF RHVFWGSG
SHTLPALLENLKL RKQNNGAFNETLFRNQLALATWTIQGAANALSGDVWDIDNEF
(SEQ ID NO: 105).

[00075] An example non-human primate transferrin receptor amino acid sequence, corresponding to NCBI sequence NP_001244232.1(transferrin receptor protein 1, *Macaca mulatta*) is as follows:

MMDQARSASFNLFGGEPLSYTRFSLARQVDGDN SHVEMKLG VDEEENTDNNTKPNGT
KPKRCGGNICYGTIAVIIFFLIGFMIGYLG YCKGVEPKTECERLAGTESPAREEPEEDFPA
APRLYWDDLKRKLSEKLDTTDFTSTIKLLNENLYVPREAGSQKDENLALYIENQFREFK
LSKVWRDQH FVKIQVKDSAQNSVIIVDKNGGLVYLVENPGGYVAYS KAATVTGKL VH
ANFGTKKDFEDLDSPVNGSIVIVRAGKITFAEKVANAESLNAIGVLIYMDQTKFPIVKAD
LSFFGHAHLGTGDPYTPGFPSFNHTQFP SQSSGLPNIPVQTISR AAAEKLFGNMEGDCPS
DWKTDSTCKMVTSENKSVKLT VSNVLKETKILNIFGVIKGFVEPDHYVVVGAQRDAW
GPGAAGSSVGTALLLKL AQMFSDMV LKDG FQPSRSIIFASWSAGDFG SVGATEWLEGY
LSSLHLKAFTYINLDKAVLGTSNFKVSASPLLYTLIEKTMQDVKHPVTGRSLYQDSNWA
SKVEKLTLDNAAFPFLAYSGIPAVSFCFCEDTDYPYLGT TMDTYKELVERIPELNKVAR
AAAEVAGQFVIKLTHDTELNLDYERYNSQLLLFLRDLNQYRADVKEMGLSLQWLYSA

RGDFFRATSRLTTDFRNAEKRDKFVMKKLNDRVMRVEYYFLSPYVSPKESPFRHVFHWG
SGSHTLSALLESLKLRRQNNSAFNETLFRNQLALATWTIQGAANALSGDVWDIDNEF
(SEQ ID NO: 106)

[00076] An example non-human primate transferrin receptor amino acid sequence, corresponding to NCBI sequence XP_005545315.1 (transferrin receptor protein 1, *Macaca fascicularis*) is as follows:

MMDQARSASFNLFGGEPLSYTRFSLARQVDGDN SHVEMKLGVD E EENTDNNTKANGT
KPKRCGGNICYGTIAVIIFFLIGFMIGYLG YCKGVEPKTECERLAGTESPAREEPEEDFPA
APRLYWDDLKRKLSEKLDTTDFTSTIKLLNENLYVPREAGS QKDENLALYIENQFREFK
LSKVWRDQHFVKIQVKDS AQNSVIIVDKNGGLVYLVENPGGYVAYS KAATVTGKLVH
ANFGTKKDFEDLDSPVNGSIVIVRAGKITFAEKVANAESLNAIGVLIYMDQTKFPIVKAD
LSFFGHAHLGTGDPYTPGFPSFNHTQFPQS QSSGLPNIPVQTISR AAAEKLFGNMEGDCPS
DWKTDSTCKMVTSENKSVKLT VSNVLKETKILNIFGVIKGFVEPDHYVVVGAQRDAW
GPGA AKSSVGTALLKL A QMFSDMV LKDG FQPSRSIIFASWSAGDFG SVGATEWLEGY
LSSLHLKAFTYINLDKAVLGTSNFKVSASPLLYTLIEKTMQDV KHPVTGRSLYQDSNWA
SKVEKLTLDNAAFPFLAYSGIPAVSFCFCEDTDYPYLGTTMDTYKELVERIPELNKVAR
AAAEVAGQFVIKLT HDTELNDYERYNSQLLLFLRDLNQYRADVKEMGLSLQWL YSA
RGDFFRATSRLTTDFRNAEKRDKFVMKKLNDRVMRVEYYFLSPYVSPKESPFRHVFHWG
SGSHTLSALLESLKLRRQNNSAFNETLFRNQLALATWTIQGAANALSGDVWDIDNEF
(SEQ ID NO: 107).

[00077] An example mouse transferrin receptor amino acid sequence, corresponding to NCBI sequence NP_001344227.1 (transferrin receptor protein 1, *Mus musculus*) is as follows:

MMDQARSASFNLFGGEPLSYTRFSLARQVDGDN SHVEMKLAAD E EENADNNMKASV
RKPKRFNGRLCFAAIALVIFFLIGFMSGYLG YCKRVEQKEECVKLAETEETDKSETMETE
DVPTSSRLYWADLKTLLSEKLN SIEFADTIKQLSQNTYTPREAGS QKDESLAYYIENQFH
EFKFSKVWRDEHYVKIQVKSSIGQNMVTIVQSNGNLDPVESPEGYVAFSKPTEVSGKLV
HANFGTKKDFEELSYSVNGSLVIVRAGEITFAEKVANAQSFNAIGVLIYMDKNKFPVVE
ADLALFGHAHLGTGDPYTPGFPSFNHTQFPQS QSSGLPNIPVQTISR AAAEKLFGKMEGS
CPARWNIDSSCKLELSQNQNVKLIVKNVLKERRILNIFGVIKGYEEPDRYVVVGAQRDA
LGAGVAAKSSVGTGLLLKL A QVFSDMISKDGF RPSRSIIFASWTAGDFG AVGATEWLEG
YLSSLHLKAFTYINLDKVVLGTSNFKVSASPLLYTLMGKIMQDV KHPVDGKSLYRDSN
WISKVEKLSFDNAAYPFLAYSGIPAVSFCFCEDADYPYLGTRLDTYEALTQKVPQLNQM
VRTAAEVAGQLIKLT HDVELNDYEMYNSKLLSFMKDLNQFKTDIRDMGLSLQWL YS
ARGDYFRATSRLTTDFHNAEKTNR FVMREINDRIMKVEYHFLSPYVSPRESPFRHIFHWG
SGSHTLSALVENLKL RQKNITAFNETLFRNQLALATWTIQGVANALSGDIWNIDNEF

(SEQ ID NO: 108)

[00078] In some embodiments, an anti-TfR1 antibody binds to an amino acid segment of the receptor as follows:

FVKIQVKDSAQNSVIIVDKNGRLVYLVENPGGYVAYSKAATVTGKLVHANFGTKKDFE
DLYTPVNGSIVIVRAGKITFAEKVANAESLNAIGVLIYMDQTKFPIVNAELSFFGHAHLG
TGDPYTPGFPSFNHTQFPPSRSSGLPNIPVQTISRAAAEKLFGNMEGDCPSDWKTDSTCR
MVTSESKNVKLTVSNVLKE (SEQ ID NO: 109) and does not inhibit the binding interactions between transferrin receptors and transferrin and/or (e.g., and) human hemochromatosis protein (also known as HFE). In some embodiments, the anti-TfR1 antibody described herein does not bind an epitope in SEQ ID NO: 109.

[00079] Appropriate methodologies may be used to obtain and/or (e.g., and) produce antibodies, antibody fragments, or antigen-binding agents, e.g., through the use of recombinant DNA protocols. In some embodiments, an antibody may also be produced through the generation of hybridomas (see, e.g., Kohler, G and Milstein, C. “Continuous cultures of fused cells secreting antibody of predefined specificity” *Nature*, 1975, 256: 495-497). The antigen-of-interest may be used as the immunogen in any form or entity, e.g., recombinant or a naturally occurring form or entity. Hybridomas are screened using standard methods, e.g., ELISA screening, to find at least one hybridoma that produces an antibody that targets a particular antigen. Antibodies may also be produced through screening of protein expression libraries that express antibodies, e.g., phage display libraries. Phage display library design may also be used, in some embodiments, (see, e.g. U.S. Patent No 5,223,409, filed 3/1/1991, “Directed evolution of novel binding proteins”; WO 1992/18619, filed 4/10/1992, “Heterodimeric receptor libraries using phagemids”; WO 1991/17271, filed 5/1/1991, “Recombinant library screening methods”; WO 1992/20791, filed 5/15/1992, “Methods for producing members of specific binding pairs”; WO 1992/15679, filed 2/28/1992, and “Improved epitope displaying phage”). In some embodiments, an antigen-of-interest may be used to immunize a non-human animal, e.g., a rodent or a goat. In some embodiments, an antibody is then obtained from the non-human animal, and may be optionally modified using a number of methodologies, e.g., using recombinant DNA techniques. Additional examples of antibody production and methodologies are known in the art (see, e.g., Harlow et al. “Antibodies: A Laboratory Manual”, Cold Spring Harbor Laboratory, 1988.).

[00080] In some embodiments, an antibody is modified, e.g., modified via glycosylation, phosphorylation, sumoylation, and/or (e.g., and) methylation. In some embodiments, an antibody is a glycosylated antibody, which is conjugated to one or more sugar or carbohydrate molecules. In some embodiments, the one or more sugar or carbohydrate molecule are

conjugated to the antibody via N-glycosylation, O-glycosylation, C-glycosylation, glypiation (GPI anchor attachment), and/or (e.g., and) phosphoglycosylation. In some embodiments, the one or more sugar or carbohydrate molecules are monosaccharides, disaccharides, oligosaccharides, or glycans. In some embodiments, the one or more sugar or carbohydrate molecule is a branched oligosaccharide or a branched glycan. In some embodiments, the one or more sugar or carbohydrate molecule includes a mannose unit, a glucose unit, an N-acetylglucosamine unit, an N-acetylgalactosamine unit, a galactose unit, a fucose unit, or a phospholipid unit. In some embodiments, there are about 1-10, about 1-5, about 5-10, about 1-4, about 1-3, or about 2 sugar molecules. In some embodiments, a glycosylated antibody is fully or partially glycosylated. In some embodiments, an antibody is glycosylated by chemical reactions or by enzymatic means. In some embodiments, an antibody is glycosylated in vitro or inside a cell, which may optionally be deficient in an enzyme in the N- or O- glycosylation pathway, e.g., a glycosyltransferase. In some embodiments, an antibody is functionalized with sugar or carbohydrate molecules as described in International Patent Application Publication WO2014065661, published on May 1, 2014, entitled, “*Modified antibody, antibody-conjugate and process for the preparation thereof*”.

[00081] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VL domain and/or (e.g., and) VH domain of any one of the anti-TfR1 antibodies selected from any one of **Tables 2-7**, and comprises a constant region comprising the amino acid sequences of the constant regions of an IgG, IgE, IgM, IgD, IgA or IgY immunoglobulin molecule, any class (e.g., IgG1, IgG2, IgG3, IgG4, IgA1 and IgA2), or any subclass (e.g., IgG2a and IgG2b) of immunoglobulin molecule. Non-limiting examples of human constant regions are described in the art, e.g., see Kabat E A et al., (1991) *supra*.

[00082] In some embodiments, agents binding to transferrin receptor, e.g., anti-TfR1 antibodies, are capable of targeting muscle cell and/or (e.g., and) mediate the transportation of an agent across the blood brain barrier. Transferrin receptors are internalizing cell surface receptors that transport transferrin across the cellular membrane and participate in the regulation and homeostasis of intracellular iron levels. Some aspects of the disclosure provide transferrin receptor binding proteins, which are capable of binding to transferrin receptor. Antibodies that bind, e.g., specifically bind, to a transferrin receptor may be internalized into the cell, e.g., through receptor-mediated endocytosis, upon binding to a transferrin receptor.

[00083] Provided herein, in some aspects, are humanized antibodies that bind to transferrin receptor with high specificity and affinity. In some embodiments, the humanized anti-TfR1 antibody described herein specifically binds to any extracellular epitope of a transferrin receptor or an epitope that becomes exposed to an antibody. In some embodiments,

the humanized anti-TfR1 antibodies provided herein bind specifically to transferrin receptor from human, non-human primates, mouse, rat, *etc.* In some embodiments, the humanized anti-TfR1 antibodies provided herein bind to human transferrin receptor. In some embodiments, the humanized anti-TfR1 antibody described herein binds to an amino acid segment of a human or non-human primate transferrin receptor, as provided in SEQ ID NOs: 105-108. In some embodiments, the humanized anti-TfR1 antibody described herein binds to an amino acid segment corresponding to amino acids 90-96 of a human transferrin receptor as set forth in SEQ ID NO: 105, which is not in the apical domain of the transferrin receptor. In some embodiments, the humanized anti-TfR1 antibodies described herein binds to TfR1 but does not bind to TfR2.

[00084] In some embodiments, the anti-TfR1 antibodies described herein (e.g., Anti-TfR1 clone 8 in Table 2 below) bind an epitope in TfR1, wherein the epitope comprises residues in amino acids 214-241 and/or amino acids 354-381 of SEQ ID NO: 105. In some embodiments, the anti-TfR1 antibodies described herein bind an epitope comprising residues in amino acids 214-241 and amino acids 354-381 of SEQ ID NO: 105. In some embodiments, the anti-TfR1 antibodies described herein bind an epitope comprising one or more of residues Y222, T227, K231, H234, T367, S368, S370, T376, and S378 of human TfR1 as set forth in SEQ ID NO: 105. In some embodiments, the anti-TfR1 antibodies described herein bind an epitope comprising residues Y222, T227, K231, H234, T367, S368, S370, T376, and S378 of human TfR1 as set forth in SEQ ID NO: 105.

[00085] In some embodiments, the anti-TfR1 antibody described herein (e.g., 3M12 in Table 2 below and its humanized variants) bind an epitope in TfR1, wherein the epitope comprises residues in amino acids 258-291 and/or amino acids 358-381 of SEQ ID NO: 105. In some embodiments, the anti-TfR1 antibodies (e.g., 3M12 in Table 2 below and its humanized variants) described herein bind an epitope comprising residues in amino acids amino acids 258-291 and amino acids 358-381 of SEQ ID NO: 105. In some embodiments, the anti-TfR1 antibodies described herein (e.g., 3M12 in Table 2 below and its humanized variants) bind an epitope comprising one or more of residues K261, S273, Y282, T362, S368, S370, and K371 of human TfR1 as set forth in SEQ ID NO: 105. In some embodiments, the anti-TfR1 antibodies described herein (e.g., 3M12 in Table 2 below and its humanized variants) bind an epitope comprising residues K261, S273, Y282, T362, S368, S370, and K371 of human TfR1 as set forth in SEQ ID NO: 105.

[00086] In some embodiments, an anti-TfR1 antibody specifically binds a TfR1 (e.g., a human or non-human primate TfR1) with binding affinity (e.g., as indicated by Kd) of at least about 10^{-4} M, 10^{-5} M, 10^{-6} M, 10^{-7} M, 10^{-8} M, 10^{-9} M, 10^{-10} M, 10^{-11} M, 10^{-12} M, 10^{-13} M, or less.

In some embodiments, the anti-TfR1 antibodies described herein bind to TfR1 with a KD of sub-nanomolar range. In some embodiments, the anti-TfR1 antibodies described herein selectively bind to transferrin receptor 1 (TfR1) but do not bind to transferrin receptor 2 (TfR2). In some embodiments, the anti-TfR1 antibodies described herein bind to human TfR1 and cyno TfR1 (e.g., with a Kd of 10^{-7} M, 10^{-8} M, 10^{-9} M, 10^{-10} M, 10^{-11} M, 10^{-12} M, 10^{-13} M, or less), but do not bind to a mouse TfR1. The affinity and binding kinetics of the anti-TfR1 antibody can be tested using any suitable method including but not limited to biosensor technology (e.g., OCTET or BIACORE). In some embodiments, binding of any one of the anti-TfR1 antibodies described herein does not complete with or inhibit transferrin binding to the TfR1. In some embodiments, binding of any one of the anti-TfR1 antibodies described herein does not complete with or inhibit HFE-beta-2-microglobulin binding to the TfR1.

[00087] Non-limiting examples of anti-TfR1 antibodies are provided in **Table 2**.

Table 2. Examples of Anti-TfR1 Antibodies

Ab	No. system	IMGT	Kabat	Chothia
3-A4	CDR-H1	GFNIKDDY (SEQ ID NO: 1)	DDYMY (SEQ ID NO: 7)	GFNIKDD (SEQ ID NO: 12)
	CDR-H2	IDPENGDT (SEQ ID NO: 2)	WIDPENGDT EYASKFQD (SEQ ID NO: 8)	ENG (SEQ ID NO: 13)
	CDR-H3	TLWLRRGLDY (SEQ ID NO: 3)	WLRRGLDY (SEQ ID NO: 9)	LRRGLD (SEQ ID NO: 14)
	CDR-L1	KSLHNSGYTY (SEQ ID NO: 4)	RSSKSLHNSGYTYLF (SEQ ID NO: 10)	SKSLHNSGYTY (SEQ ID NO: 15)
	CDR-L2	RMS (SEQ ID NO: 5)	RMSNLAS (SEQ ID NO: 11)	RMS (SEQ ID NO: 5)
	CDR-L3	MQHLEYPFT (SEQ ID NO: 6)	MQHLEYPFT (SEQ ID NO: 6)	HLEYPF (SEQ ID NO: 16)
	VH	EVQLQQSGAELVRPGASVKLSCTASGFNIKDDYMYWVKQRPEQGLEWIGWIDPENGDT EYASKFQDKATVTADTSSNTAYLQLSSLTSEDTAVYYCTLWLRRGLDYWGQGTSVTVS S (SEQ ID NO: 17)		
	VL	DIVMTQAAPSPVPTPGESVSISCRSSKSLHNSGYTYLFWFLQRPQGSPQLLIYRMSNLA SGVPDRFSGSGSGTAFTLRISRVEAEDVGVYYCMQHLEYPFTFGGGTKLEIK (SEQ ID NO: 18)		
3-A4 N54T*	CDR-H1	GFNIKDDY (SEQ ID NO: 1)	DDYMY (SEQ ID NO: 7)	GFNIKDD (SEQ ID NO: 12)
	CDR-H2	IDPETGDT (SEQ ID NO: 19)	WIDPETGDTEYASKFQD (SEQ ID NO: 20)	ETG (SEQ ID NO: 21)
	CDR-H3	TLWLRRGLDY (SEQ ID NO: 3)	WLRRGLDY (SEQ ID NO: 9)	LRRGLD (SEQ ID NO: 14)
	CDR-L1	KSLHNSGYTY (SEQ ID NO: 4)	RSSKSLHNSGYTYLF (SEQ ID NO: 10)	SKSLHNSGYTY (SEQ ID NO: 15)

	CDR-L2	RMS (SEQ ID NO: 5)	RMSNLAS (SEQ ID NO: 11)	RMS(SEQ ID NO: 5)
	CDR-L3	MQHLEYPFT (SEQ ID NO: 6)	MQHLEYPFT (SEQ ID NO: 6)	HLEYPF (SEQ ID NO: 16)
	VH	EVQLQQSGAELVRPGASVKLSCTASGFNIKDDYMYWVKQRPEQGLEWIGWIDPETGDT EYASKFQDKATVTADTSSNTAYLQLSSLTSEDTAVYYCTLWLRRLDYWGQGTSTVTS S (SEQ ID NO: 22)		
	VL	DIVMTQAAPSVPVTPGESVSISCRSSKSLLSNGYTYLFWFLQRPQGSPQLLIYRMSNLA SGVPDRFSGSGSGTAFTLRISRVEAEDVGVYYCMQHLEYPFTFGGGTKLEIK (SEQ ID NO: 18)		
3-A4 N54S*	CDR-H1	GFNIKDDY (SEQ ID NO: 1)	DDYMY (SEQ ID NO: 7)	GFNIKDD (SEQ ID NO: 12)
	CDR-H2	IDPESGDT (SEQ ID NO: 23)	WIDPESGDTEYASKFQD (SEQ ID NO: 24)	ESG (SEQ ID NO: 25)
	CDR-H3	TLWLRRLDY (SEQ ID NO: 3)	WLRRLDY (SEQ ID NO: 9)	LRRGLD (SEQ ID NO: 14)
	CDR-L1	KSLLSNGYTY (SEQ ID NO: 4)	RSSKSLLSNGYTYLF (SEQ ID NO: 10)	SKSLLSNGYTY (SEQ ID NO: 15)
	CDR-L2	RMS (SEQ ID NO: 5)	RMSNLAS (SEQ ID NO: 11)	RMS (SEQ ID NO: 5)
	CDR-L3	MQHLEYPFT (SEQ ID NO: 6)	MQHLEYPFT (SEQ ID NO: 6)	HLEYPF (SEQ ID NO: 16)
	VH	EVQLQQSGAELVRPGASVKLSCTASGFNIKDDYMYWVKQRPEQGLEWIGWIDPESGDT EYASKFQDKATVTADTSSNTAYLQLSSLTSEDTAVYYCTLWLRRLDYWGQGTSTVTS S (SEQ ID NO: 26)		
	VL	DIVMTQAAPSVPVTPGESVSISCRSSKSLLSNGYTYLFWFLQRPQGSPQLLIYRMSNLA SGVPDRFSGSGSGTAFTLRISRVEAEDVGVYYCMQHLEYPFTFGGGTKLEIK (SEQ ID NO: 18)		
3-M12	CDR-H1	GYSITSGYY (SEQ ID NO: 27)	SGYYWN (SEQ ID NO: 33)	GYSITSGY (SEQ ID NO: 38)
	CDR-H2	ITFDGAN (SEQ ID NO: 28)	YITFDGANNYNPSLKN (SEQ ID NO: 34)	FDG (SEQ ID NO: 39)
	CDR-H3	TRSSYDYDVL DY (SEQ ID NO: 29)	SSYDYDVL DY (SEQ ID NO: 35)	SYDYDVL DY (SEQ ID NO: 40)
	CDR-L1	QDISNF (SEQ ID NO: 30)	RASQDISNFLN (SEQ ID NO: 36)	SQDISNF (SEQ ID NO: 41)
	CDR-L2	YTS (SEQ ID NO: 31)	YTSRLHS (SEQ ID NO: 37)	YTS (SEQ ID NO: 31)
	CDR-L3	QQGHTLPYT (SEQ ID NO: 32)	QQGHTLPYT (SEQ ID NO: 32)	GHTLPY (SEQ ID NO: 42)
	VH	DVQLQESGPGLVKPSQSLSTCSVTGYSITSGYYWNWIRQFPGNKLEWMGYITFDGAN NYNPSLKNRISITRDTSKNQFFLKLTSVTEDTATYYCTRSSYDYDVL DYWGQGTTLV SS (SEQ ID NO: 43)		
	VL	DIQMTQTSSLSASLGDRVTISCRASQDISNFLNWWYQQRPDGTVKLLIYYTSRLHSGVPS RFSGSGSGTDFSLTVSNLEQEDIATYFCQQGHTLPYTFGGGTKLEIK (SEQ ID NO: 44)		
5-H12	CDR-H1	GYSFTDYC (SEQ ID NO: 45)	DYCIN (SEQ ID NO: 51)	GYSFTDY (SEQ ID NO: 56)

	CDR-H2	IYPGSGNT (SEQ ID NO: 46)	WIYPGSGNTRYSERFKG (SEQ ID NO: 52)	GSG (SEQ ID NO: 57)
	CDR-H3	AREDYYPYHGMDY (SEQ ID NO: 47)	EDYYPYHGMDY (SEQ ID NO: 53)	DYYPYHGMD (SEQ ID NO: 58)
	CDR-L1	ESVDGYDNSF (SEQ ID NO: 48)	RASESVDGYDNSFMH (SEQ ID NO: 54)	SESVDGYDNSF (SEQ ID NO: 59)
	CDR-L2	RAS (SEQ ID NO: 49)	RASNLES (SEQ ID NO: 55)	RAS (SEQ ID NO: 49)
	CDR-L3	QQSSEDPWT (SEQ ID NO: 50)	QQSSEDPWT (SEQ ID NO: 50)	SSEDPW (SEQ ID NO: 60)
	VH	QIQLQQSGPELVPRGASVKISCKASGYSFTDYCINWVNQRPGQGLEWIGWIYPGSGNTRYSERFKGKATLTVDTSSNTAYMQLSSLTSEDSAVYFCAREDYYPYHGMDYWGQGTSVTVSS (SEQ ID NO: 61)		
	VL	DIVLTQSPTSLAVSLGQRATISCRASESVDGYDNSFMHWYQQKPGQPPKLLIFRASNLES GIPARFSGSGSRTDFTLTINPVEAADVATYYCQQSSEDPWTFGGGTTKLEIK (SEQ ID NO: 62)		
5-H12 C33Y*	CDR-H1	GYSFTDYY (SEQ ID NO: 63)	DYYIN (SEQ ID NO: 64)	GYSFTDY (SEQ ID NO: 56)
	CDR-H2	IYPGSGNT (SEQ ID NO: 46)	WIYPGSGNTRYSERFKG (SEQ ID NO: 52)	GSG (SEQ ID NO: 57)
	CDR-H3	AREDYYPYHGMDY (SEQ ID NO: 47)	EDYYPYHGMDY (SEQ ID NO: 53)	DYYPYHGMD (SEQ ID NO: 58)
	CDR-L1	ESVDGYDNSF (SEQ ID NO: 48)	RASESVDGYDNSFMH (SEQ ID NO: 54)	SESVDGYDNSF (SEQ ID NO: 59)
	CDR-L2	RAS (SEQ ID NO: 49)	RASNLES (SEQ ID NO: 55)	RAS (SEQ ID NO: 49)
	CDR-L3	QQSSEDPWT (SEQ ID NO: 50)	QQSSEDPWT (SEQ ID NO: 50)	SSEDPW (SEQ ID NO: 60)
	VH	QIQLQQSGPELVPRGASVKISCKASGYSFTDYYINWVNQRPGQGLEWIGWIYPGSGNTRYSERFKGKATLTVDTSSNTAYMQLSSLTSEDSAVYFCAREDYYPYHGMDYWGQGTSVTVSS (SEQ ID NO: 65)		
	VL	DIVLTQSPTSLAVSLGQRATISCRASESVDGYDNSFMHWYQQKPGQPPKLLIFRASNLES GIPARFSGSGSRTDFTLTINPVEAADVATYYCQQSSEDPWTFGGGTTKLEIK (SEQ ID NO: 62)		
5-H12 C33D*	CDR-H1	GYSFTDYD (SEQ ID NO: 66)	DYDIN (SEQ ID NO: 67)	GYSFTDY (SEQ ID NO: 56)
	CDR-H2	IYPGSGNT (SEQ ID NO: 46)	WIYPGSGNTRYSERFKG (SEQ ID NO: 52)	GSG (SEQ ID NO: 57)
	CDR-H3	AREDYYPYHGMDY (SEQ ID NO: 47)	EDYYPYHGMDY (SEQ ID NO: 53)	DYYPYHGMD (SEQ ID NO: 58)
	CDR-L1	ESVDGYDNSF (SEQ ID NO: 48)	RASESVDGYDNSFMH (SEQ ID NO: 54)	SESVDGYDNSF (SEQ ID NO: 59)
	CDR-L2	RAS (SEQ ID NO: 49)	RASNLES (SEQ ID NO: 55)	RAS (SEQ ID NO: 49)
	CDR-L3	QQSSEDPWT (SEQ ID NO: 50)	QQSSEDPWT (SEQ ID NO: 50)	SSEDPW (SEQ ID NO: 60)

	VH	QIQLQQSGPELVPRPGASVKISCKASGYSFTDYDINWVNQRPGQGLEWIGWIYPGSGNTRY SERFKGKATLTVDTSSNTAYMQLSSLTSEDSAVYFCAREDDYYPYHGMDYWGQGTSTVTV SS (SEQ ID NO: 68)		
	VL	DIVLTQSPTSLAVSLGQRATISCRASESVDGYDNSFMHWYQQKPGQPPKLLIFRASNLES GIPARFSGSGSRTDFTLTINPVEAADVATYYCQQSSEDPWTFGGGKLEIK (SEQ ID NO: 62)		
Anti-TfR1 clone 8	CDR-H1	GYSFTSYW (SEQ ID NO: 138)	SYWIG (SEQ ID NO: 144)	GYSFTSY (SEQ ID NO: 149)
	CDR-H2	IYPGDSDT (SEQ ID NO: 139)	IYPGDS DTRYSPSFQGQ (SEQ ID NO: 145)	GDS (SEQ ID NO: 150)
	CDR-H3	ARFPYDSSGYYSFDY (SEQ ID NO: 140)	FPYDSSGYYSFDY (SEQ ID NO: 146)	PYDSSGYYSFD (SEQ ID NO: 151)
	CDR-L1	QSISSY (SEQ ID NO: 141)	RASQSISSYLN (SEQ ID NO: 147)	SQSISSY (SEQ ID NO: 152)
	CDR-L2	AAS (SEQ ID NO: 142)	AASSLQS (SEQ ID NO: 148)	AAS (SEQ ID NO: 142)
	CDR-L3	QQSYSTPLT (SEQ ID NO: 143)	QQSYSTPLT (SEQ ID NO: 143)	SYSTPL (SEQ ID NO: 153)

* mutation positions are according to Kabat numbering of the respective VH sequences containing the mutations

[00088] In some embodiments, the anti-TfR1 antibody of the present disclosure is a humanized variant of any one of the anti-TfR1 antibodies provided in **Table 2**. In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a CDR-H1, a CDR-H2, a CDR-H3, a CDR-L1, a CDR-L2, and a CDR-L3 that are the same as the CDR-H1, CDR-H2, and CDR-H3 in any one of the anti-TfR1 antibodies provided in **Table 2**, and comprises a humanized heavy chain variable region and/or (e.g., and) a humanized light chain variable region.

[00089] Examples of amino acid sequences of anti-TfR1 antibodies described herein are provided in **Table 3**.

Table 3. Variable Regions of Anti-TfR1 Antibodies

Antibody	Variable Region Amino Acid Sequence**
3A4 VH3 (N54T*)/Vκ4	V _H : EVQLVQSGSELKKPGASVKVSTASGFNIK DDYMYWVRQPPGKGLEWIGWIDP ETGDTEYASKFQDRVTVTADTSTNTAYMELSSLRSEDTAVYYCTLWLRRGLD YWGQGTLVTVSS (SEQ ID NO: 69)
	V _L : DIVMTQSPLSLPVTPGEPASISCRSSK SLLSNGYTYLFWFQQRPGQSPRLLIYR MSNLASGVPDRFSGSGSGTDFTLKISRVEAEDVGVYYCMQHLEYPTFTGGGK VEIK (SEQ ID NO: 70)
3A4 VH3 (N54S*)/Vκ4	V _H : EVQLVQSGSELKKPGASVKVSTASGFNIK DDYMYWVRQPPGKGLEWIGWIDP ESGDTEYASKFQDRVTVTADTSTNTAYMELSSLRSEDTAVYYCTLWLRRGLD YWGQGTLVTVSS (SEQ ID NO: 71)
	V _L : DIVMTQSPLSLPVTPGEPASISCRSSK SLLSNGYTYLFWFQQRPGQSPRLLIYR MSNLASGVPDRFSGSGSGTDFTLKISRVEAEDVGVYYCMQHLEYPTFTGGGK VEIK (SEQ ID NO: 70)
3A4	V _H :

Antibody	Variable Region Amino Acid Sequence**
VH3 /Vκ4	EVQLVQSGSELKKPGASVKVSTASGFNIKDDYMYWVRQPPGKGLEWIGWIDP ENGDT EYASKFQDR VTVTADTSTNTAYMELSSLRSEDTAVYYCTL WLRRGLD YWGQGTLLTVSS (SEQ ID NO: 72)
	VL: DIVMTQSPLSLPVTTPGEPASISCRSSK SLLS NGYTYLFWFQQRPGQSPRLLIYR MSNLASGVDPDRFSGSGSGTDFTLKISRVEAEDVGVYYCM QHLEY PFTFGGGTK VEIK (SEQ ID NO: 70)
3M12 VH3/Vκ2	VH: QVQLQESGPGLVKPSQTLSTCSVTGYSTIT SGYYWN WIRQPPGKGLEWMGYITF DGANNYN PSLKN RVSISRDTSKNQFSLKLSSVTAEDTATYYCTR SSYDYD VLDY WGQGTITVTVSS (SEQ ID NO: 73)
	VL: DIQMTQSPSSLSASVGDRVITITCRASQ DISN FLNWYQQKPGQPVKLLIY YTSRLH SGVPSRFSGSGSGTDFTLTISSLQPEDFATYYC QQGHTL PYTFGQGTKLEIK (SEQ ID NO: 74)
3M12 VH3/Vκ3	VH: QVQLQESGPGLVKPSQTLSTCSVTGYSTIT SGYYWN WIRQPPGKGLEWMGYITF DGANNYN PSLKN RVSISRDTSKNQFSLKLSSVTAEDTATYYCTR SSYDYD VLDY WGQGTITVTVSS (SEQ ID NO: 73)
	VL: DIQMTQSPSSLSASVGDRVITITCRASQ DISN FLNWYQQKPGQPVKLLIY YTSRLH SGVPSRFSGSGSGTDFTLTISSLQPEDFATYYC QQGHTL PYTFGQGTKLEIK (SEQ ID NO: 75)
3M12 VH4/Vκ2	VH: QVQLQESGPGLVKPSQTLSTCTVTGYSTIT SGYYWN WIRQPPGKGLEWIGYITFD GANNYN PSLKN RVSISRDTSKNQFSLKLSSVTAEDTATYYCTR SSYDYD VLDYW GQGTITVTVSS (SEQ ID NO: 76)
	VL: DIQMTQSPSSLSASVGDRVITITCRASQ DISN FLNWYQQKPGQPVKLLIY YTSRLH SGVPSRFSGSGSGTDFTLTISSLQPEDFATYYC QQGHTL PYTFGQGTKLEIK (SEQ ID NO: 74)
3M12 VH4/Vκ3	VH: QVQLQESGPGLVKPSQTLSTCTVTGYSTIT SGYYWN WIRQPPGKGLEWIGYITFD GANNYN PSLKN RVSISRDTSKNQFSLKLSSVTAEDTATYYCTR SSYDYD VLDYW GQGTITVTVSS (SEQ ID NO: 76)
	VL: DIQMTQSPSSLSASVGDRVITITCRASQ DISN FLNWYQQKPGQPVKLLIY YTSRLH SGVPSRFSGSGSGTDFTLTISSLQPEDFATYYC QQGHTL PYTFGQGTKLEIK (SEQ ID NO: 75)
5H12 VH5 (C33Y*)/Vκ3	VH: QVQLVQSGAEVKKPGASVKVSKASGYSTFDYYINWVRQAPGQGLEWMGWIIY PGSGNTRYSER FKGR VTITRDTASTAYMELSSLRSEDTAVYYCARE DYPPYH GMDYWGQGTLLTVSS (SEQ ID NO: 77)
	VL: DIVLTQSPDSLAVSLGERATINCRASE VDGYD NSFMHWYQQKPGQPPKLLIFR ASNLESGVPDRFSGSGSRDFTLTISSLQAEDVAVYYC QQSSED PWTFGQGTKL EIK (SEQ ID NO: 78)
5H12 VH5 (C33D*)/Vκ4	VH: QVQLVQSGAEVKKPGASVKVSKASGYSTFDYDINWVRQAPGQGLEWMGWIIY PGSGNTRYSER FKGR VTITRDTASTAYMELSSLRSEDTAVYYCARE DYPPYH GMDYWGQGTLLTVSS (SEQ ID NO: 79)
	VL: DIVMTQSPDSLAVSLGERATINCRASE VDGYD NSFMHWYQQKPGQPPKLLIFR ASNLESGVPDRFSGSGSGTDFTLTISSLQAEDVAVYYC QQSSED PWTFGQGTKL EIK (SEQ ID NO: 80)
5H12 VH5 (C33Y*)/Vκ4	VH: QVQLVQSGAEVKKPGASVKVSKASGYSTFDYYINWVRQAPGQGLEWMGWIIY PGSGNTRYSER FKGR VTITRDTASTAYMELSSLRSEDTAVYYCARE DYPPYH GMDYWGQGTLLTVSS (SEQ ID NO: 77)

Antibody	Variable Region Amino Acid Sequence**
	VL: DIVMTQSPDSLAVSLGERATINCRASESDVDGYDNSFMHWYQQKPGQPPKLLIFR ASNLESGVPDRFSGSGSGTDFTLTISSLQAEDVAVYYC QQSSEDPWTF GQGTKL EIK (SEQ ID NO: 80)
Anti-TfR1 clone 8	VH: QVQLVQSGAEVKKPGESLKISCKGSGYSFTSYWIGWVRQMPGKGLEWMGIIYP GDS DT RYSPSFQGQ VTISADKSISTAYLQWSSLKASDTAMY ¹⁰⁰ YCARFPYDSSGY ¹⁰⁵ Y SFDY WGQGTLLTVSS (SEQ ID NO: 154)
	VL: DIQMTQSPSSLSASVGDRVTITCRASQSISSYLNWYQQKPGKAPKLLIYAASSLQ SGVPSRFSGSGSGTDFTLTISSLQPEDFATYYC QQSYSTPLT FGGGTKVEIK (SEQ ID NO: 155)

* mutation positions are according to Kabat numbering of the respective VH sequences containing the mutations

** CDRs according to the Kabat numbering system are bolded

[00090] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VH comprising the CDR-H1, CDR-H2, and CDR-H3 of any one of the anti-TfR1 antibodies provided in **Table 3** and comprises one or more (e.g., 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 or more) amino acid variations in the framework regions as compared with the respective humanized VH provided in **Table 3**. Alternatively or in addition (e.g., in addition), the anti-TfR1 antibody of the present disclosure comprises a VL comprising the CDR-L1, CDR-L2, and CDR-L3 of any one of the anti-TfR1 antibodies provided in **Table 3** and comprises one or more (e.g., 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 or more) amino acid variations in the framework regions as compared with the respective humanized VL provided in **Table 3**.

[00091] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VH comprising the CDR-H1, CDR-H2, and CDR-H3 of any one of the anti-TfR1 antibodies provided in **Table 3** and comprising an amino acid sequence that is at least 70% (e.g., at least 70%, at least 75%, at least 80%, at least 85%, at least 90%, at least 95%, at least 99%) identical in the framework regions as compared with the respective VH provided in **Table 3**. Alternatively or in addition (e.g., in addition), the anti-TfR1 antibody of the present disclosure comprises a VL comprising the CDR-L1, CDR-L2, and CDR-L3 of any one of the anti-TfR1 antibodies provided in **Table 3** and comprising an amino acid sequence that is at least 70% (e.g., at least 70%, at least 75%, at least 80%, at least 85%, at least 90%, at least 95%, at least 99%) identical in the framework regions compared with the respective VL provided in **Table 3**.

[00092] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VH comprising the amino acid sequence of SEQ ID NO: 69 and a VL comprising the amino acid sequence of SEQ ID NO: 70.

[00093] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VH comprising the amino acid sequence of SEQ ID NO: 71 and a VL comprising the amino acid sequence of SEQ ID NO: 70.

[00094] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VH comprising the amino acid sequence of SEQ ID NO: 72 and a VL comprising the amino acid sequence of SEQ ID NO: 70.

[00095] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VH comprising the amino acid sequence of SEQ ID NO: 73 and a VL comprising the amino acid sequence of SEQ ID NO: 74.

[00096] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VH comprising the amino acid sequence of SEQ ID NO: 73 and a VL comprising the amino acid sequence of SEQ ID NO: 75.

[00097] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VH comprising the amino acid sequence of SEQ ID NO: 76 and a VL comprising the amino acid sequence of SEQ ID NO: 74.

[00098] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VH comprising the amino acid sequence of SEQ ID NO: 76 and a VL comprising the amino acid sequence of SEQ ID NO: 75.

[00099] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VH comprising the amino acid sequence of SEQ ID NO: 77 and a VL comprising the amino acid sequence of SEQ ID NO: 78.

[000100] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VH comprising the amino acid sequence of SEQ ID NO: 79 and a VL comprising the amino acid sequence of SEQ ID NO: 80.

[000101] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VH comprising the amino acid sequence of SEQ ID NO: 77 and a VL comprising the amino acid sequence of SEQ ID NO: 80.

[000102] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VH comprising the amino acid sequence of SEQ ID NO: 154 and a VL comprising the amino acid sequence of SEQ ID NO: 155.

[000103] In some embodiments, the anti-TfR1 antibody described herein is a full-length IgG, which can include a heavy constant region and a light constant region from a human antibody. In some embodiments, the heavy chain of any of the anti-TfR1 antibodies as described herein may comprise a heavy chain constant region (CH) or a portion thereof (e.g., CH1, CH2, CH3, or a combination thereof). The heavy chain constant region can be of any suitable origin, e.g., human, mouse, rat, or rabbit. In one specific example, the heavy chain constant region is from a human IgG (a gamma heavy chain), e.g., IgG1, IgG2, or IgG4. An example of a human IgG1 constant region is given below:

ASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGALTSGVHTFPAVLQSSGLYSLSVVTVPSSSLGTQTYICNVNHKPSNTKVDKKVEPKSCDKTHTCPPCPAPELLGPSVFLFPPKPKDTLMISRTPEVTCVVDVSHEDPEVKFNWYVDGVEVHNAKTKPREEQYNSTYRVVSVLTVLHQDWLNGKEYKCKVSNKALPAPIEKTISKAKGQPREPQVYTLPPSRDELTKNQVSLTCLVKGFYPSDIAVEWESNGQPENNYKTTPPVLDSDGSFFLYSKLTVDKSRWQQGNVVFSCSVMHEALHNHYTQKSLSLSPGK (SEQ ID NO: 81)

[000104] In some embodiments, the heavy chain of any of the anti-TfR1 antibodies described herein comprises a mutant human IgG1 constant region. For example, the introduction of LALA mutations (a mutant derived from mAb b12 that has been mutated to replace the lower hinge residues Leu234 Leu235 with Ala234 and Ala235) in the CH2 domain of human IgG1 is known to reduce Fcγ receptor binding (Bruhns, P., et al. (2009) and Xu, D. et al. (2000)). The mutant human IgG1 constant region is provided below (mutations bonded and underlined):

ASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGALTSGVHTFPAVLQSSGLYSLSVVTVPSSSLGTQTYICNVNHKPSNTKVDKKVEPKSCDKTHTCPPCPAPEAAGGPSVFLFPPKPKDTLMISRTPEVTCVVDVSHEDPEVKFNWYVDGVEVHNAKTKPREEQYNSTYRVVSVLTVLHQDWLNGKEYKCKVSNKALPAPIEKTISKAKGQPREPQVYTLPPSRDELTKNQVSLTCLVKGFYPSDIAVEWESNGQPENNYKTTPPVLDSDGSFFLYSKLTVDKSRWQQGNVVFSCSVMHEALHNHYTQKSLSLSPGK (SEQ ID NO: 82)

[000105] In some embodiments, the light chain of any of the anti-TfR1 antibodies described herein may further comprise a light chain constant region (CL), which can be any CL known in the art. In some examples, the CL is a kappa light chain. In other examples, the CL is a lambda light chain. In some embodiments, the CL is a kappa light chain, the sequence of which is provided below:

RTVAAPSVFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQESVTEQDSKDSTYLSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC (SEQ ID NO: 83)

[000106] Other antibody heavy and light chain constant regions are well known in the art, e.g., those provided in the IMGT database (www.imgt.org) or at www.vbase2.org/vbstat.php, both of which are incorporated by reference herein.

[000107] In some embodiments, the anti-TfR1 antibody described herein comprises a heavy chain comprising any one of the VH as listed in **Table 3** or any variants thereof and a heavy chain constant region that is at least 80%, at least 85%, at least 90%, at least 95%, or at least 99% identical to SEQ ID NO: 81 or SEQ ID NO: 82. In some embodiments, the anti-TfR1 antibody described herein comprises a heavy chain comprising any one of the VH as listed in **Table 3** or any variants thereof and a heavy chain constant region that contains no more than 25

amino acid variations (e.g., no more than 25, 24, 23, 22, 21, 20, 19, 18, 17, 16, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, or 1 amino acid variation) as compared with SEQ ID NO: 81 or SEQ ID NO: 82. In some embodiments, the anti-TfR1 antibody described herein comprises a heavy chain comprising any one of the VH as listed in **Table 3** or any variants thereof and a heavy chain constant region as set forth in SEQ ID NO: 81. In some embodiments, the anti-TfR1 antibody described herein comprises heavy chain comprising any one of the VH as listed in **Table 3** or any variants thereof and a heavy chain constant region as set forth in SEQ ID NO: 82.

[000108] In some embodiments, the anti-TfR1 antibody described herein comprises a light chain comprising any one of the VL as listed in **Table 3** or any variants thereof and a light chain constant region that is at least 80%, at least 85%, at least 90%, at least 95%, or at least 99% identical to SEQ ID NO: 83. In some embodiments, the anti-TfR1 antibody described herein comprises a light chain comprising any one of the VL as listed in **Table 3** or any variants thereof and a light chain constant region contains no more than 25 amino acid variations (e.g., no more than 25, 24, 23, 22, 21, 20, 19, 18, 17, 16, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, or 1 amino acid variation) as compared with SEQ ID NO: 83. In some embodiments, the anti-TfR1 antibody described herein comprises a light chain comprising any one of the VL as listed in **Table 3** or any variants thereof and a light chain constant region set forth in SEQ ID NO: 83.

[000109] Examples of IgG heavy chain and light chain amino acid sequences of the anti-TfR1 antibodies described are provided in **Table 4** below.

Table 4. Heavy chain and light chain sequences of examples of anti-TfR1 IgGs

Antibody	IgG Heavy Chain/Light Chain Sequences**
3A4 VH3 (N54T*)/Vκ4	Heavy Chain (with wild type human IgG1 constant region) <u>EVQLVQSGSELKKPGASVKVSTASGFNIKDDYMYWVRQPPGKGLEWIGWIDPE</u> <u>TGDEYASKFQDRVTVTADTSTNTAYMELSSLRSED</u> <u>AVYYCTLWLRRLDYW</u> <u>GQGT</u> <u>LVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVT</u> <u>TSWNSGAL</u> <u>TSGVHTFPAVLQSSGLYSLSSVTV</u> <u>PSSSLGTQTYICNVNHKPSNTKVDKKVEPKS</u> <u>CDK</u> <u>TH</u> <u>TCPPCPAPELLGGPSVFLFPPKPKDTLMISRTPEVTCVVVDVSHEDPEVKFN</u> <u>WYVDGVEVHNAKTKPREEQYNSTYRVSVLT</u> <u>VLHQDWLNGKEYKCKVSNKALP</u> <u>APIEKTISKAKGQPREPVYTLPPSRDELTKNQVSLTCLVKGFYPSDIAVEWESNGQ</u> <u>PENNYKTTTPVLDS</u> <u>SGSFFLYSKLTVDKSRWQQGNVFSCSVMHEALHNHYTQKSL</u> <u>SLSPGK</u> (SEQ ID NO: 84)
	Light Chain (with kappa light chain constant region) <u>DIVMTQSPLSLPVTPGEPASISCRSSKSLLSHNGYTYLFWFQORPGQSPRLLIYRMS</u> <u>NLASGV</u> <u>PDRFSGSGSGTDFTLKISRVEAEDVGVYYCMQHLEYPFTFGGGTKVEIK</u> <u>RTVAAPS</u> <u>VFIFPPSDEQLKSGTASV</u> <u>VCLLN</u> <u>NFYPREAKVQWKVDNALQSGNSQES</u> <u>VTEQDSK</u> <u>DSTYLSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC</u> (SEQ ID NO: 85)
3A4 VH3 (N54S*)/Vκ4	Heavy Chain (with wild type human IgG1 constant region) <u>EVQLVQSGSELKKPGASVKVSTASGFNIKDDYMYWVRQPPGKGLEWIGWIDPE</u> <u>SGDTEYASKFQDRVTVTADTSTNTAYMELSSLRSED</u> <u>AVYYCTLWLRRLDYW</u> <u>GQGT</u> <u>LVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVT</u> <u>TSWNSGAL</u> <u>TSGVHTFPAVLQSSGLYSLSSVTV</u> <u>PSSSLGTQTYICNVNHKPSNTKVDKKVEPKS</u> <u>CDK</u> <u>TH</u> <u>TCPPCPAPELLGGPSVFLFPPKPKDTLMISRTPEVTCVVVDVSHEDPEVKFN</u>

Antibody	IgG Heavy Chain/Light Chain Sequences**
	WYVDGVEVHNAKTKPREEQYNSTYRVVSVLTVLHQDWLNGKEYKCKVSNKALPAPIEKTISKAKGQPREPQVYTLPPSRDELTKNQVSLTCLVKGFYPSDIAVEWESNGQPENNYKTTTPVLDSDGSFFLYSKLTVDKSRWQQGNVFSCSVMEALHNHYTQKSLSLSPGK (SEQ ID NO: 86) Light Chain (with kappa light chain constant region) <u>DIVMTQSPLSLPVTGPGEASISCRSSKSLHSNGYTYLFWFOORPGQSPRLLIYRMSNLASGVDPDRFSGSGSGTDFTLKISRVEAEDVGVYYCMQHLEYPTFGGGTKVEIKRTVAAPSVMFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQESVTEQDSKDYSLSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC</u> (SEQ ID NO: 85)
3A4 VH3/Vκ4	Heavy Chain (with wild type human IgG1 constant region) <u>EVQLVQSGSELKPGASVKVSTASGFNIKDDYMYWVRQPPGKGLEWIGWIDPENGDTEYASKFQDRVTVTADTSTNTAYMELSSLRSEDTAVYYCTLWLRRLDYWGQGTLVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGALTSGVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHKPSNTKVDKKVEPKSCDKTHTCPPCPAPELLGGPSVFLFPPKPKDTLMISRTPEVTCVVDVSHEDPEVKFNWYVDGVEVHNAKTKPREEQYNSTYRVVSVLTVLHQDWLNGKEYKCKVSNKALPAPIEKTISKAKGQPREPQVYTLPPSRDELTKNQVSLTCLVKGFYPSDIAVEWESNGQPENNYKTTTPVLDSDGSFFLYSKLTVDKSRWQQGNVFSCSVMEALHNHYTQKSLSLSPGK</u> (SEQ ID NO: 87) Light Chain (with kappa light chain constant region) <u>DIVMTQSPLSLPVTGPGEASISCRSSKSLHSNGYTYLFWFOORPGQSPRLLIYRMSNLASGVDPDRFSGSGSGTDFTLKISRVEAEDVGVYYCMQHLEYPTFGGGTKVEIKRTVAAPSVMFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQESVTEQDSKDYSLSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC</u> (SEQ ID NO: 85)
3M12 VH3/Vκ2	Heavy Chain (with wild type human IgG1 constant region) <u>QVQLQESGPGLVKPSQTLSTCSVTGYSITSGYYWNWIROPFGKGLEWMGYITFDGANNYNPSLKNRVSISRDTSKNQFSLKLSSVTAEDTATYYCTRSSYDYDVLDDYWGQGTITVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGALTSGVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHKPSNTKVDKKVEPKSCDKTHTCPPCPAPELLGGPSVFLFPPKPKDTLMISRTPEVTCVVDVSHEDPEVKFNWYVDGVEVHNAKTKPREEQYNSTYRVVSVLTVLHQDWLNGKEYKCKVSNKALPAPIEKTISKAKGQPREPQVYTLPPSRDELTKNQVSLTCLVKGFYPSDIAVEWESNGQPENNYKTTTPVLDSDGSFFLYSKLTVDKSRWQQGNVFSCSVMEALHNHYTQKSLSLSPGK</u> (SEQ ID NO: 88) Light Chain (with kappa light chain constant region) <u>DIQMTQSPSSLSASVGDRVITTCRASQDISNFLNWYQOKPGOPVKLLIYYTSRLHS</u> <u>GVPSRFSGSGSGTDFTLTISLQPEDFATYFCQOGHTLPYTFGQGTGLEIKRTVAAPSVFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQESVTEQDSKDYSLSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC</u> (SEQ ID NO: 89)
3M12 VH3/Vκ3	Heavy Chain (with wild type human IgG1 constant region) <u>QVQLQESGPGLVKPSQTLSTCSVTGYSITSGYYWNWIROPFGKGLEWMGYITFDGANNYNPSLKNRVSISRDTSKNQFSLKLSSVTAEDTATYYCTRSSYDYDVLDDYWGQGTITVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGALTSGVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHKPSNTKVDKKVEPKSCDKTHTCPPCPAPELLGGPSVFLFPPKPKDTLMISRTPEVTCVVDVSHEDPEVKFNWYVDGVEVHNAKTKPREEQYNSTYRVVSVLTVLHQDWLNGKEYKCKVSNKALPAPIEKTISKAKGQPREPQVYTLPPSRDELTKNQVSLTCLVKGFYPSDIAVEWESNGQPENNYKTTTPVLDSDGSFFLYSKLTVDKSRWQQGNVFSCSVMEALHNHYTQKSLSLSPGK</u> (SEQ ID NO: 88) Light Chain (with kappa light chain constant region) <u>DIQMTQSPSSLSASVGDRVITTCRASQDISNFLNWYQOKPGOPVKLLIYYTSRLHS</u> <u>GVPSRFSGSGSGTDFTLTISLQPEDFATYFCQOGHTLPYTFGQGTGLEIKRTVAAPSVMFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQESVTEQDSKDYSLSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC</u> (SEQ ID NO: 90)
3M12 VH4/Vκ2	Heavy Chain (with wild type human IgG1 constant region) <u>QVQLQESGPGLVKPSQTLSTCTVTGYSITSGYYWNWIROPFGKGLEWIGYITFDGANNYNPSLKNRVSISRDTSKNQFSLKLSSVTAEDTATYYCTRSSYDYDVLDDYWGQGTITVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGALT</u>

Antibody	IgG Heavy Chain/Light Chain Sequences**
	GVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHNKPSNTKVDKKVEPKSCD KTHTCPPCPAPELLGGPSVFLFPPKPKDTLMISRTPEVTCVVVDVSHEDPEVKFNW YVDGVEVHNAKTKPREEQYNSTYRVVSVLTVLHQDWLNGKEYKCKVSNKALPA PIEKTISKAKGQPREPQVYTLPPSRDELTKNQVSLTCLVKGFYPSDIAVEWESNGQP ENNYKTTTPVLDSDGSFFLYSKLTVDKSRWQQGNVFCSCVMHEALHNHYTQKSLS LSPGK (SEQ ID NO: 91) Light Chain (with kappa light chain constant region) <u>DIQMTQSPSSLSASVGDRVITTCRASQDISNFLNHWYQOKPGQPVKLLIYYTSRLHS</u> <u>GVPSRFGSGSGTDFLTITSLQPEDFATYFCQOGHTLPYTFGQGTKLEIKRTVAAP</u> <u>SVFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQESVTEQDSK</u> <u>DSTYLSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC</u> (SEQ ID NO: 89)
3M12 VH4/Vκ3	Heavy Chain (with wild type human IgG1 constant region) <u>QVQLQESGPGLVKPSQTLSTCTVTGYSITSGYYWNWIRPPGKGLEWIGYITFDG</u> <u>ANNYNPSLKNRVSISRDTSKNQFSLKLSSVTAEDTATYYCTRSSYDYDVLDYWGQ</u> <u>GTTVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGALTS</u> GVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHNKPSNTKVDKKVEPKSCD KTHTCPPCPAPELLGGPSVFLFPPKPKDTLMISRTPEVTCVVVDVSHEDPEVKFNW YVDGVEVHNAKTKPREEQYNSTYRVVSVLTVLHQDWLNGKEYKCKVSNKALPA PIEKTISKAKGQPREPQVYTLPPSRDELTKNQVSLTCLVKGFYPSDIAVEWESNGQP ENNYKTTTPVLDSDGSFFLYSKLTVDKSRWQQGNVFCSCVMHEALHNHYTQKSLS LSPGK (SEQ ID NO: 91) Light Chain (with kappa light chain constant region) <u>DIQMTQSPSSLSASVGDRVITTCRASQDISNFLNHWYQOKPGQPVKLLIYYTSRLHS</u> <u>GVPSRFGSGSGTDFLTITSLQPEDFATYYCQOGHTLPYTFGQGTKLEIKRTVAA</u> <u>PSVFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQESVTEQDS</u> <u>KDSTYLSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC</u> (SEQ ID NO: 90)
5H12 VH5 (C33Y*)/Vκ3	Heavy Chain (with wild type human IgG1 constant region) <u>QVQLVQSGAEVKKPGASVKVSCKASGYSTFDYYINWVRQAPGQGLEWMGWIYP</u> <u>GSNTRYSERFKGRVTITRDTASTAYMELSSLRSEDTAVYYCAREDYYPYHGM</u> <u>DYWGQGTLLTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWN</u> SGALTSGVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHNKPSNTKVDKKV EPKSCDKTHTCPPCPAPELLGGPSVFLFPPKPKDTLMISRTPEVTCVVVDVSHEDPE VKFNWYVDGVEVHNAKTKPREEQYNSTYRVVSVLTVLHQDWLNGKEYKCKVSN KALPAPIEKTISKAKGQPREPQVYTLPPSRDELTKNQVSLTCLVKGFYPSDIAVEWE SNGQPENNYKTTTPVLDSDGSFFLYSKLTVDKSRWQQGNVFCSCVMHEALHNHYT QKSLSLSPGK (SEQ ID NO: 92) Light Chain (with kappa light chain constant region) <u>DIVLTQSPDSLAVSLGERATINCRASESDVDGYDNSFMHWYQOKPGOPPKLLIFRAS</u> <u>NLESGVPDRFSGSGRTDFLTITSLQAEDVAVYYCQOQSEDPWTFGQGTKLEIKR</u> <u>TVAAPSVFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQESV</u> <u>TEQDSKDSTYLSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC</u> (SEQ ID NO: 93)
5H12 VH5 (C33D*)/Vκ4	Heavy Chain (with wild type human IgG1 constant region) <u>QVQLVQSGAEVKKPGASVKVSCKASGYSTFDYDINWVRQAPGQGLEWMGWIYP</u> <u>GSNTRYSERFKGRVTITRDTASTAYMELSSLRSEDTAVYYCAREDYYPYHGM</u> <u>DYWGQGTLLTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWN</u> SGALTSGVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHNKPSNTKVDKKV EPKSCDKTHTCPPCPAPELLGGPSVFLFPPKPKDTLMISRTPEVTCVVVDVSHEDPE VKFNWYVDGVEVHNAKTKPREEQYNSTYRVVSVLTVLHQDWLNGKEYKCKVSN KALPAPIEKTISKAKGQPREPQVYTLPPSRDELTKNQVSLTCLVKGFYPSDIAVEWE SNGQPENNYKTTTPVLDSDGSFFLYSKLTVDKSRWQQGNVFCSCVMHEALHNHYT QKSLSLSPGK (SEQ ID NO: 94) Light Chain (with kappa light chain constant region) <u>DIVMTQSPDSLAVSLGERATINCRASESDVDGYDNSFMHWYQOKPGOPPKLLIFRA</u> <u>SNLESGVPDRFSGSGSGTDFLTITSLQAEDVAVYYCQOQSEDPWTFGQGTKLEIK</u> <u>RTVAAPSVFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQES</u> <u>VTEQDSKDSTYLSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC</u> (SEQ ID NO: 95)
5H12	Heavy Chain (with wild type human IgG1 constant region)

Antibody	IgG Heavy Chain/Light Chain Sequences**
VH5 (C33Y*)/VK4	<u>QVQLVQSGAEVKKPGASVKVSCKASGYSFTDYYINWVRQAPGQGLEWMGWIYP</u> <u>CSGNTRYSERFKGRVTITRDTSA</u><u>STAYMELSSLRSEDTAVYYCARE</u><u>DYYPYHGM</u> <u>DYWGQGT</u><u>LVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWN</u> <u>SGALTSGVHTFPAVLQSSGLYSLSSVTV</u><u>PSSSLGTQTYICNVNHKPSNTKVDKKV</u> <u>EPKSCDKTHTCPPCPAPELLGGPSVFLFPPKPKDTLMISRTPEVTCVVDVSHEDPE</u> <u>VKFNWYVDGVEVHNAKTKPREEQYNSTYRVVSVLTVLHQDWLNGKEYKCKVSN</u> <u>KALPAPIEKTISKAKGQPREPQVYTLPPSRDELTKNQVSLTCLVKGFYPSDIAVEWE</u> <u>SNGQPENNYKTTPPVLDSDGSFFLYSKLTV</u><u>DKSRWQQGNVFSCSVMHEALHNHYT</u> <u>QKSLSLSPGK</u> (SEQ ID NO: 92) Light Chain (with kappa light chain constant region): <u>DIVMTQSPDSLAVSLGERATINCRASESV</u><u>DGYDNSFMHWYQOKPGOPPKLLIFRA</u> <u>SNLESGVPDRFSGSGSGTDFTLT</u><u>ISSLOAEDVAVYYCQO</u><u>SSDPWTFGQGTKLEIK</u> <u>RTVAAPS</u><u>VFIFPPSDEQLKSGTASV</u><u>VCLLN</u><u>FYPREAKVQWKVDNALQSGNSQES</u> <u>VTEQDSK</u><u>DSTYLSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC</u> (SEQ ID NO: 95)
Anti-TfR1 clone 8	Heavy Chain (with wild type human IgG1 constant region): <u>QVQLVQSGAEVKKPGESLKISCKGSGYSFTSYWIGWVROMPGKGLEWMGHIYPG</u> <u>DS</u><u>TRYSPSFOGQVTISADKSISTAYLOWSSLKASDTAMYYCARFPYDSSGYYSF</u> <u>DYWGQGT</u><u>LVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWN</u> <u>SGALTSGVHTFPAVLQSSGLYSLSSVTV</u><u>PSSSLGTQTYICNVNHKPSNTKVDKKV</u> <u>EPKSCDKTHTCPPCPAPELLGGPSVFLFPPKPKDTLMISRTPEVTCVVDVSHEDPE</u> <u>VKFNWYVDGVEVHNAKTKPREEQYNSTYRVVSVLTVLHQDWLNGKEYKCKVSN</u> <u>KALPAPIEKTISKAKGQPREPQVYTLPPSRDELTKNQVSLTCLVKGFYPSDIAVEWE</u> <u>SNGQPENNYKTTPPVLDSDGSFFLYSKLTV</u><u>DKSRWQQGNVFSCSVMHEALHNHYT</u> <u>QKSLSLSPGK</u> (SEQ ID NO: 156) Light Chain (with kappa light chain constant region): <u>DIQMTQSPSSLSASVGDRVTITCRASQSISSYLNWYQOKPGKAPKLLIYAASSLOS</u> <u>GVPSRFSGSGSGTDFTLT</u><u>ISSLOPEDFATYYCQO</u><u>SYSTPLTFGGG</u><u>TKVEIKRTVAAP</u> <u>SVFIFPPSDEQLKSGTASV</u><u>VCLLN</u><u>FYPREAKVQWKVDNALQSGNSQESVTEQDSK</u> <u>DSTYLSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC</u> (SEQ ID NO: 157)

* mutation positions are according to Kabat numbering of the respective VH sequences containing the mutations

** CDRs according to the Kabat numbering system are bolded; VH/VL sequences underlined

[000110] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain containing no more than 25 amino acid variations (e.g., no more than 25, 24, 23, 22, 21, 20, 19, 18, 17, 16, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, or 1 amino acid variation) as compared with the heavy chain as set forth in any one of SEQ ID NOs: 84, 86, 87, 88, 91, 92, 94, and 156. Alternatively or in addition (e.g., in addition), the anti-TfR1 antibody of the present disclosure comprises a light chain containing no more than 25 amino acid variations (e.g., no more than 25, 24, 23, 22, 21, 20, 19, 18, 17, 16, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, or 1 amino acid variation) as compared with the light chain as set forth in any one of SEQ ID NOs: 85, 89, 90, 93, 95, and 157.

[000111] In some embodiments, the anti-TfR1 antibody described herein comprises a heavy chain comprising an amino acid sequence that is at least 75% (e.g., 75%, 80%, 85%, 90%, 95%, 98%, or 99%) identical to any one of SEQ ID NOs: 84, 86, 87, 88, 91, 92, 94, and 156. Alternatively or in addition (e.g., in addition), the anti-TfR1 antibody described herein comprises a light chain comprising an amino acid sequence that is at least 75% (e.g., 75%, 80%, 85%, 90%, 95%, 98%, or 99%) identical to any one of SEQ ID NOs: 85, 89, 90, 93, 95, and 157.

In some embodiments, the anti-TfR1 antibody described herein comprises a heavy chain comprising the amino acid sequence of any one of SEQ ID NOs: 84, 86, 87, 88, 91, 92, 94, and 156. Alternatively or in addition (e.g., in addition), the anti-TfR1 antibody described herein comprises a light chain comprising the amino acid sequence of any one of SEQ ID NOs: 85, 89, 90, 93, 95 and 157.

[000112] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 84 and a light chain comprising the amino acid sequence of SEQ ID NO: 85.

[000113] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 86 and a light chain comprising the amino acid sequence of SEQ ID NO: 85.

[000114] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 87 and a light chain comprising the amino acid sequence of SEQ ID NO: 85.

[000115] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 88 and a light chain comprising the amino acid sequence of SEQ ID NO: 89.

[000116] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 88 and a light chain comprising the amino acid sequence of SEQ ID NO: 90.

[000117] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 91 and a light chain comprising the amino acid sequence of SEQ ID NO: 89.

[000118] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 91 and a light chain comprising the amino acid sequence of SEQ ID NO: 90.

[000119] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 92 and a light chain comprising the amino acid sequence of SEQ ID NO: 93.

[000120] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 94 and a light chain comprising the amino acid sequence of SEQ ID NO: 95.

[000121] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 92 and a light chain comprising the amino acid sequence of SEQ ID NO: 95.

[000122] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 156 and a light chain comprising the amino acid sequence of SEQ ID NO: 157.

[000123] In some embodiments, the anti-TfR1 antibody is a Fab fragment, Fab' fragment, or F(ab')₂ fragment of an intact antibody (full-length antibody). Antigen binding fragment of an intact antibody (full-length antibody) can be prepared via routine methods (e.g., recombinantly or by digesting the heavy chain constant region of a full-length IgG using an enzyme such as papain). For example, F(ab')₂ fragments can be produced by pepsin or papain digestion of an antibody molecule, and Fab fragments that can be generated by reducing the disulfide bridges of F(ab')₂ fragments. In some embodiments, a heavy chain constant region in a Fab fragment of the anti-TfR1 antibody described herein comprises the amino acid sequence of:

ASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGALTSGVHTFPAVLQSSGLYSLSSVVTVPSSSLGTQTYICNVNHKPSNTKVDKKVEPKSCDKTHT (SEQ ID NO: 96)

[000124] In some embodiments, the anti-TfR1 antibody described herein comprises a heavy chain comprising any one of the VH as listed in **Table 3** or any variants thereof and a heavy chain constant region that is at least 80%, at least 85%, at least 90%, at least 95%, or at least 99% identical to SEQ ID NO: 96. In some embodiments, the anti-TfR1 antibody described herein comprises a heavy chain comprising any one of the VH as listed in **Table 3** or any variants thereof and a heavy chain constant region that contains no more than 25 amino acid variations (e.g., no more than 25, 24, 23, 22, 21, 20, 19, 18, 17, 16, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, or 1 amino acid variation) as compared with SEQ ID NO: 96. In some embodiments, the anti-TfR1 antibody described herein comprises a heavy chain comprising any one of the VH as listed in **Table 3** or any variants thereof and a heavy chain constant region as set forth in SEQ ID NO: 96.

[000125] In some embodiments, the anti-TfR1 antibody described herein comprises a light chain comprising any one of the VL as listed in **Table 3** or any variants thereof and a light chain constant region that is at least 80%, at least 85%, at least 90%, at least 95%, or at least 99% identical to SEQ ID NO: 83. In some embodiments, the anti-TfR1 antibody described herein comprises a light chain comprising any one of the VL as listed in **Table 3** or any variants thereof and a light chain constant region contains no more than 25 amino acid variations (e.g., no more than 25, 24, 23, 22, 21, 20, 19, 18, 17, 16, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, or 1 amino acid variation) as compared with SEQ ID NO: 83. In some embodiments, the anti-TfR1 antibody described herein comprises a light chain comprising any one of the VL as listed in **Table 3** or any variants thereof and a light chain constant region set forth in SEQ ID NO: 83.

[000126] Examples of Fab heavy chain and light chain amino acid sequences of the anti-TfR1 antibodies described are provided in **Table 5** below.

Table 5. Heavy chain and light chain sequences of examples of anti-TfR1 Fabs

Antibody	Fab Heavy Chain/Light Chain Sequences**
3A4 VH3 (N54T*)/Vκ4	Heavy Chain (with partial human IgG1 constant region) <u>EVQLVQSGSELKKPGASVKV</u> SCTASGFNIK DDYMYWVR QPPGKGLEWIG WIDPE TGDTEYASKFQDR VTVTADTSTNTAYMELSSLRSEDTAVYYCTL WLRRLD YW <u>GQGT</u> LVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGAL TSGVHTFPAVLQSSGLYSLSSVTVTPSSSLGTQTYICNVNHKPSNTKVDKKVEPKS CDKHT (SEQ ID NO: 97)
	Light Chain (with kappa light chain constant region) DIVMTQSPLSLPVT PGEPASISCRSSKSL HSNGYTYLFWFQORPGQSPRLLIY RMS NLAS GVDPDRFSGSGSGTDFTLKISRVEAEDVGVYY CMOHLEYP FTFGGGTKVEIK RTVAAPSVFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQES VTEQDSKDYSLSSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC (SEQ ID NO: 85)
3A4 VH3 (N54S*)/Vκ4	Heavy Chain (with partial human IgG1 constant region) <u>EVQLVQSGSELKKPGASVKV</u> SCTASGFNIK DDYMYWVR QPPGKGLEWIG WIDPE SGDTEYASKFQDR VTVTADTSTNTAYMELSSLRSEDTAVYYCTL WLRRLD YW <u>GQGT</u> LVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGAL TSGVHTFPAVLQSSGLYSLSSVTVTPSSSLGTQTYICNVNHKPSNTKVDKKVEPKS CDKHT (SEQ ID NO: 98)
	Light Chain (with kappa light chain constant region) DIVMTQSPLSLPVT PGEPASISCRSSKSL HSNGYTYLFWFQORPGQSPRLLIY RMS NLAS GVDPDRFSGSGSGTDFTLKISRVEAEDVGVYY CMOHLEYP FTFGGGTKVEIK RTVAAPSVFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQES VTEQDSKDYSLSSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC (SEQ ID NO: 85)
3A4 VH3 /Vκ4	Heavy Chain (with partial human IgG1 constant region) <u>EVQLVQSGSELKKPGASVKV</u> SCTASGFNIK DDYMYWVR QPPGKGLEWIG WIDPE NGDTEYASKFQDR VTVTADTSTNTAYMELSSLRSEDTAVYYCTL WLRRLD YW <u>GQGT</u> LVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGAL TSGVHTFPAVLQSSGLYSLSSVTVTPSSSLGTQTYICNVNHKPSNTKVDKKVEPKS CDKHT (SEQ ID NO: 99)
	Light Chain (with kappa light chain constant region) DIVMTQSPLSLPVT PGEPASISCRSSKSL HSNGYTYLFWFQORPGQSPRLLIY RMS NLAS GVDPDRFSGSGSGTDFTLKISRVEAEDVGVYY CMOHLEYP FTFGGGTKVEIK RTVAAPSVFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQES VTEQDSKDYSLSSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC (SEQ ID NO: 85)
3M12 VH3/Vκ2	Heavy Chain (with partial human IgG1 constant region) <u>QVQLQESG</u> PGLVKPSQTL SLTCSVTGYSITSGYYWN WIRQPPGKGLEWMGY ITFD GANNYNPSLKN RVISIRDTSKNQFSLKLSSVTAEDTATYYCTR SSYDYDVLDYWG <u>QGT</u> TVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGALT SGVHTFPAVLQSSGLYSLSSVTVTPSSSLGTQTYICNVNHKPSNTKVDKKVEPKSC DKHT (SEQ ID NO: 100)
	Light Chain (with kappa light chain constant region) DIQMTQSPSSLSASVGDRVT ITCRASODISN FLNWYQOKPGQPVKLLIY YTSRLHS <u>GVPSR</u> FSGSGSGTDFTLTISLQPEDFATYFC QOGHTLPY TFGQGTKLEIKRTVAAP SVFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQESVTEQDSK DYSLSSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC (SEQ ID NO: 89)
3M12 VH3/Vκ3	Heavy Chain (with partial human IgG1 constant region) <u>QVQLQESG</u> PGLVKPSQTL SLTCSVTGYSITSGYYWN WIRQPPGKGLEWMGY ITFD GANNYNPSLKN RVISIRDTSKNQFSLKLSSVTAEDTATYYCTR SSYDYDVLDYWG <u>QGT</u> TVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGALT SGVHTFPAVLQSSGLYSLSSVTVTPSSSLGTQTYICNVNHKPSNTKVDKKVEPKSC DKHT (SEQ ID NO: 100)
	Light Chain (with kappa light chain constant region)

Antibody	Fab Heavy Chain/Light Chain Sequences**
	<u>DIQMTQSPSSLSASVGDRVTTTCRASQDISNFLNWYQOKPGQPVKLLIYYTSRLHS</u> <u>GVPSRFGSGSGTDFTLTISLQPEDFATYYCQOGHTLPYTFGQGTKLEIKRTVAA</u> PSVFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQESVTEQDS KDSTYLSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC (SEQ ID NO: 90)
3M12 VH4/Vκ2	Heavy Chain (with partial human IgG1 constant region) <u>QVQLQESGPGGLVKPSQTLSTCTVTGYSITSGYYWNWIRPPGKGLEWIGYITFDG</u> <u>ANNYNPSLKNRVSI</u>SRDTSKNQFSLKLSSVTAEDTATYYCTRSSYDYDVLDDYWGQ GTTVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGALTS GVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHKPSNTKVDKKVEPKSCD KTHT (SEQ ID NO: 101) Light Chain (with kappa light chain constant region) <u>DIQMTQSPSSLSASVGDRVTTTCRASQDISNFLNWYQOKPGQPVKLLIYYTSRLHS</u> <u>GVPSRFGSGSGTDFTLTISLQPEDFATYYCQOGHTLPYTFGQGTKLEIKRTVAAP</u> SVFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQESVTEQDSK DSTYLSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC (SEQ ID NO: 89)
3M12 VH4/Vκ3	Heavy Chain (with partial human IgG1 constant region) <u>QVQLQESGPGGLVKPSQTLSTCTVTGYSITSGYYWNWIRPPGKGLEWIGYITFDG</u> <u>ANNYNPSLKNRVSI</u>SRDTSKNQFSLKLSSVTAEDTATYYCTRSSYDYDVLDDYWGQ GTTVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGALTS GVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHKPSNTKVDKKVEPKSCD KTHT (SEQ ID NO: 101) Light Chain (with kappa light chain constant region) <u>DIQMTQSPSSLSASVGDRVTTTCRASQDISNFLNWYQOKPGQPVKLLIYYTSRLHS</u> <u>GVPSRFGSGSGTDFTLTISLQPEDFATYYCQOGHTLPYTFGQGTKLEIKRTVAA</u> PSVFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQESVTEQDS KDSTYLSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC (SEQ ID NO: 90)
5H12 VH5 (C33Y*)/Vκ3	Heavy Chain (with partial human IgG1 constant region) <u>QVQLVQSGAEVKKPGASVKVSCKASGYSTFDYYINWVRQAPGQGLEWMGWIYP</u> <u>GS</u>GNTRYSERFKGRVTITRDTSASTAYMELSSLRSEDTAVYYCAREDYYPYHGM <u>DYWGQGT</u>LVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWN SGALTSGVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHKPSNTKVDKKV EPKSCDKTHT (SEQ ID NO: 102) Light Chain (with kappa light chain constant region) <u>DIVLTQSPDSLAVSLGERATINCRASESDGYDNSFMH</u>WYQOKPGQPPKLLIFRAS <u>NLESGVPDRFSGSGSR</u>TDFTLTISLQAEDVAVYYCQOSSEDPWTFGQGTKLEIKR TVAAPSVFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQESVTEQDSKDSTYLSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC (SEQ ID NO: 93)
5H12 VH5 (C33D*)/Vκ4	Heavy Chain (with partial human IgG1 constant region) <u>QVQLVQSGAEVKKPGASVKVSCKASGYSTFDYDINWVRQAPGQGLEWMGWIYP</u> <u>GS</u>GNTRYSERFKGRVTITRDTSASTAYMELSSLRSEDTAVYYCAREDYYPYHGM <u>DYWGQGT</u>LVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWN SGALTSGVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHKPSNTKVDKKV EPKSCDKTHT (SEQ ID NO: 103) Light Chain (with kappa light chain constant region) <u>DIVMTQSPDSLAVSLGERATINCRASESDGYDNSFMH</u>WYQOKPGQPPKLLIFRA <u>SNLESGVPDRFSGSGSGTDFTLTISLQAEDVAVYYCQOSSEDPWTFGQGTKLEIK</u> RTVAAPSVFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQESVTEQDSKDSTYLSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC (SEQ ID NO: 95)
5H12 VH5 (C33Y*)/Vκ4	Heavy Chain (with partial human IgG1 constant region) <u>QVQLVQSGAEVKKPGASVKVSCKASGYSTFDYYINWVRQAPGQGLEWMGWIYP</u> <u>GS</u>GNTRYSERFKGRVTITRDTSASTAYMELSSLRSEDTAVYYCAREDYYPYHGM <u>DYWGQGT</u>LVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWN SGALTSGVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHKPSNTKVDKKV EPKSCDKTHT (SEQ ID NO: 102) Light Chain (with kappa light chain constant region)

Antibody	Fab Heavy Chain/Light Chain Sequences**
	<u>DIVMTQSPDSLAVSLGERATINCRASESVDGYDNSFMHWYQQKPGQPPKLLIFRA</u> <u>SNLESGVPDRFSGSGSGTDFTLTISLSQAEDVAVYYCQOQSEDPWTFGQGTKLEIK</u> RTVAAPSVFIFPPSDEQLKSGTASVCLLNFPYAPREKRVQWKVDNALQSGNSQES VTEQDSKDYSLSSLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC (SEQ ID NO: 95)
Anti-TfR1 clone 8 Version 1	Heavy Chain (with partial human IgG1 constant region): <u>QVQLVQSGAEVKKPGESLKISCKGSGYSFTSYWIGWVRQMPGKGLEWMGIHYPG</u> <u>DS DTRYSPSFOGQVTISADKSISTAYLOWSSLKASDTAMY YCARFPYDSSGYYSF</u> <u>DYWGQGT LVT VSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWN</u> SGALTSGVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHKPSNTKVDDKKV EPKSCDKTHTCP (SEQ ID NO: 158) Light Chain (with kappa light chain constant region): <u>DIQMTQSPSSLSASVGDRVTITCRASQSISSYLNWYQQKPGKAPKLLIYAASSLOS</u> <u>GVPSRFSGSGSGTDFTLTISLQPEDFATYYCQOQSYSTPLTFGGGKTKVEIKRTVAAP</u> SVFIFPPSDEQLKSGTASVCLLNFPYAPREKRVQWKVDNALQSGNSQESVTEQDSK DSTYSLSSLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC (SEQ ID NO: 157)
Anti-TfR1 clone 8 Version 2	Heavy Chain (with partial human IgG1 constant region): <u>QVQLVQSGAEVKKPGESLKISCKGSGYSFTSYWIGWVRQMPGKGLEWMGIHYPG</u> <u>DS DTRYSPSFOGQVTISADKSISTAYLOWSSLKASDTAMY YCARFPYDSSGYYSF</u> <u>DYWGQGT LVT VSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWN</u> SGALTSGVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHKPSNTKVDDKKV EPKSCDKTHT (SEQ ID NO: 159) Light Chain (with kappa light chain constant region): <u>DIQMTQSPSSLSASVGDRVTITCRASQSISSYLNWYQQKPGKAPKLLIYAASSLOS</u> <u>GVPSRFSGSGSGTDFTLTISLQPEDFATYYCQOQSYSTPLTFGGGKTKVEIKRTVAAP</u> SVFIFPPSDEQLKSGTASVCLLNFPYAPREKRVQWKVDNALQSGNSQESVTEQDSK DSTYSLSSLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC (SEQ ID NO: 157)

* mutation positions are according to Kabat numbering of the respective VH sequences containing the mutations

** CDRs according to the Kabat numbering system are bolded; VH/VL sequences underlined

[000127] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain containing no more than 25 amino acid variations (e.g., no more than 25, 24, 23, 22, 21, 20, 19, 18, 17, 16, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, or 1 amino acid variation) as compared with the heavy chain as set forth in any one of SEQ ID NOs: 97-103, 158 and 159. Alternatively or in addition (e.g., in addition), the anti-TfR1 antibody of the present disclosure comprises a light chain containing no more than 25 amino acid variations (e.g., no more than 25, 24, 23, 22, 21, 20, 19, 18, 17, 16, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, or 1 amino acid variation) as compared with the light chain as set forth in any one of SEQ ID NOs: 85, 89, 90, 93, 95, and 157.

[000128] In some embodiments, the anti-TfR1 antibody described herein comprises a heavy chain comprising an amino acid sequence that is at least 75% (e.g., 75%, 80%, 85%, 90%, 95%, 98%, or 99%) identical to any one of SEQ ID NOs: 97-103, 158 and 159. Alternatively or in addition (e.g., in addition), the anti-TfR1 antibody described herein comprises a light chain comprising an amino acid sequence that is at least 75% (e.g., 75%, 80%, 85%, 90%, 95%, 98%, or 99%) identical to any one of SEQ ID NOs: 85, 89, 90, 93, 95, and 157. In some embodiments, the anti-TfR1 antibody described herein comprises a heavy chain comprising the

amino acid sequence of any one of SEQ ID NOs: 97-103, 158 and 159. Alternatively or in addition (e.g., in addition), the anti-TfR1 antibody described herein comprises a light chain comprising the amino acid sequence of any one of SEQ ID NOs: 85, 89, 90, 93, 95, and 157.

[000129] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 97 and a light chain comprising the amino acid sequence of SEQ ID NO: 85.

[000130] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 98 and a light chain comprising the amino acid sequence of SEQ ID NO: 85.

[000131] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 99 and a light chain comprising the amino acid sequence of SEQ ID NO: 85.

[000132] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 100 and a light chain comprising the amino acid sequence of SEQ ID NO: 89.

[000133] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 100 and a light chain comprising the amino acid sequence of SEQ ID NO: 90.

[000134] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 101 and a light chain comprising the amino acid sequence of SEQ ID NO: 89.

[000135] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 101 and a light chain comprising the amino acid sequence of SEQ ID NO: 90.

[000136] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 102 and a light chain comprising the amino acid sequence of SEQ ID NO: 93.

[000137] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 103 and a light chain comprising the amino acid sequence of SEQ ID NO: 95.

[000138] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 102 and a light chain comprising the amino acid sequence of SEQ ID NO: 95.

[000139] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 158 and a light chain comprising the amino acid sequence of SEQ ID NO: 157.

[000140] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 159 and a light chain comprising the amino acid sequence of SEQ ID NO: 157.

Other known anti-TfR1 antibodies

[000141] Any other appropriate anti-TfR1 antibodies known in the art may be used as the muscle-targeting agent in the complexes disclosed herein. Examples of known anti-TfR1 antibodies, including associated references and binding epitopes, are listed in **Table 6**. In some embodiments, the anti-TfR1 antibody comprises the complementarity determining regions (CDR-H1, CDR-H2, CDR-H3, CDR-L1, CDR-L2, and CDR-L3) of any of the anti-TfR1 antibodies provided herein, e.g., anti-TfR1 antibodies listed in **Table 6**.

Table 6 – List of anti-TfR1 antibody clones, including associated references and binding epitope information.

Antibody Clone Name	Reference(s)	Epitope / Notes
OKT9	US Patent. No. 4,364,934, filed 12/4/1979, entitled “MONOCLONAL ANTIBODY TO A HUMAN EARLY THYMOCYTE ANTIGEN AND METHODS FOR PREPARING SAME” Schneider C. et al. “Structural features of the cell surface receptor for transferrin that is recognized by the monoclonal antibody OKT9.” J Biol Chem. 1982, 257:14, 8516-8522.	Apical domain of TfR (residues 305-366 of human TfR sequence XM_052730.3, available in GenBank)
(From JCR) Clone M11 Clone M23 Clone M27 Clone B84	- WO 2015/098989, filed 12/24/2014, “Novel anti-Transferrin receptor antibody that passes through blood-brain barrier” - US Patent No. 9,994,641, filed 12/24/2014, “Novel anti-Transferrin receptor antibody that passes through blood-brain barrier”	Apical domain (residues 230-244 and 326-347 of TfR) and protease-like domain (residues 461-473)
(From Genentech) 7A4, 8A2, 15D2, 10D11, 7B10, 15G11, 16G5, 13C3,	WO 2016/081643, filed 5/26/2016, entitled “ANTI-TRANSFERRIN RECEPTOR ANTIBODIES AND METHODS OF USE”	Apical domain and non-apical regions

16G4, 16F6, 7G7, 4C2, 1B12, and 13D4	US Patent No. 9,708,406, filed 5/20/2014, "Anti-transferrin receptor antibodies and methods of use"	
(From Armagen) 8D3	- Lee et al. "Targeting Rat Anti-Mouse Transferrin Receptor Monoclonal Antibodies through Blood-Brain Barrier in Mouse" 2000, J Pharmacol. Exp. Ther., 292: 1048-1052. - US Patent App. 2010/077498, filed 9/11/2008, entitled "COMPOSITIONS AND METHODS FOR BLOOD-BRAIN BARRIER DELIVERY IN THE MOUSE"	
OX26	Haobam, B. et al. 2014. Rab17-mediated recycling endosomes contribute to autophagosome formation in response to Group A Streptococcus invasion. Cellular microbiology. 16: 1806-21.	
DF1513	Ortiz-Zapater E et al. Trafficking of the human transferrin receptor in plant cells: effects of tyrphostin A23 and brefeldin A. Plant J 48:757-70 (2006).	
1A1B2, 66IG10, MEM-189, JF0956, 29806, 1A1B2, TFRC/1818, 1E6, 66Ig10, TFRC/1059, Q1/71, 23D10, 13E4, TFRC/1149, ER-MP21, YTA74.4, BU54, 2B6, RI7 217	Commercially available anti-transferrin receptor antibodies.	Novus Biologicals 8100 Southpark Way, A-8 Littleton CO 80120
(From INSERM) BA120g	US Patent App. 2011/0311544A1, filed 6/15/2005, entitled "ANTI-CD71 MONOCLONAL ANTIBODIES AND USES THEREOF FOR TREATING MALIGNANT TUMOR CELLS"	Does not compete with OKT9
LUCA31	US Patent No. 7,572,895, filed 6/7/2004, entitled "TRANSFERRIN RECEPTOR ANTIBODIES"	"LUCA31 epitope"
(Salk Institute) B3/25 T58/30	Trowbridge, I.S. et al. "Anti-transferrin receptor monoclonal antibody and toxin-antibody conjugates affect growth of human tumour cells."	

	Nature, 1981, volume 294, pages 171–173			
R17 217.1.3, 5E9C11, OKT9 (BE0023 clone)	Commercially available anti-transferrin receptor antibodies.	BioXcell 10 Technology Dr., Suite 2B West Lebanon, NH 03784-1671 USA		
BK19.9, B3/25, T56/14 and T58/1	Gatter, K.C. et al. “Transferrin receptors in human tissues: their distribution and possible clinical relevance.” J Clin Pathol. 1983 May;36(5):539-45.			
Anti-TfR1 antibody CDRH1 (SEQ ID NO: 177) CDRH2 (SEQ ID NO: 178) CDRH3 (SEQ ID NO: 179) CDRL1 (SEQ ID NO: 180) CDRL2 (SEQ ID NO: 181) CDRL3 (SEQ ID NO: 182) VH (SEQ ID NO: 183) VL(SEQ ID NO: 184)				
Other anti-TfR1 antibody SEQ ID NOs				
	VH/ VL	CDR1	CDR2	CDR3
VH1	193	185	186	179
VH2	194	185	187	179
VH3	195	185	188	179
VH4	196	185	187	179
VL1	197	180	181	115
VL2	198	180	181	115
VL3	199	180	190	182
VL4	200	191	192	182

[000142] In some embodiments, anti-TfR1 antibodies of the present disclosure include one or more of the CDR-H (*e.g.*, CDR-H1, CDR-H2, and CDR-H3) amino acid sequences from any one of the anti-TfR1 antibodies selected from **Table 6**. In some embodiments, anti-TfR1 antibodies include the CDR-L1, CDR-L2, and CDR-L3 as provided for any one of the anti-TfR1 antibodies selected from **Table 6**. In some embodiments, anti-TfR1 antibodies include the CDR-H1, CDR-H2, CDR-H3, CDR-L1, CDR-L2, and CDR-L3 as provided for any one of the anti-TfR1 antibodies selected from **Table 6**.

[000143] In some embodiments, anti-TfR1 antibodies of the disclosure include any antibody that includes a heavy chain variable domain and/or (*e.g.*, and) a light chain variable domain of any anti-TfR1 antibody, such as any one of the anti-TfR1 antibodies selected from **Table 6**. In some embodiments, anti-TfR1 antibodies of the disclosure include any antibody

that includes the heavy chain variable and light chain variable pairs of any anti-TfR1 antibody, such as any one of the anti-TfR1 antibodies selected from **Table 6**.

[000144] Aspects of the disclosure provide anti-TfR1 antibodies having a heavy chain variable (VH) and/or (e.g., and) a light chain variable (VL) domain amino acid sequence homologous to any of those described herein. In some embodiments, the anti-TfR1 antibody comprises a heavy chain variable sequence or a light chain variable sequence that is at least 75% (e.g., 80%, 85%, 90%, 95%, 98%, or 99%) identical to the heavy chain variable sequence and/or any light chain variable sequence of any anti-TfR1 antibody, such as any one of the anti-TfR1 antibodies selected from **Table 6**. In some embodiments, the homologous heavy chain variable and/or (e.g., and) a light chain variable amino acid sequences do not vary within any of the CDR sequences provided herein. For example, in some embodiments, the degree of sequence variation (e.g., 75%, 80%, 85%, 90%, 95%, 98%, or 99%) may occur within a heavy chain variable and/or (e.g., and) a light chain variable sequence excluding any of the CDR sequences provided herein. In some embodiments, any of the anti-TfR1 antibodies provided herein comprise a heavy chain variable sequence and a light chain variable sequence that comprises a framework sequence that is at least 75%, 80%, 85%, 90%, 95%, 98%, or 99% identical to the framework sequence of any anti-TfR1 antibody, such as any one of the anti-TfR1 antibodies selected from **Table 6**.

[000145] An example of a transferrin receptor antibody that may be used in accordance with the present disclosure is described in International Application Publication WO 2016/081643, incorporated herein by reference. The amino acid sequences of this antibody are provided in **Table 7**.

Table 7. Heavy chain and light chain CDRs of an example of a known anti-TfR1 antibody

Sequence Type	Kabat	Chothia	Contact
CDR-H1	SYWMH (SEQ ID NO: 110)	GYTFTSY (SEQ ID NO: 116)	TSYWMH (SEQ ID NO: 118)
CDR-H2	EINPTNGRTNYIE KFKS (SEQ ID NO: 111)	NPTNGR (SEQ ID NO: 117)	WIGEINPTNGRTN (SEQ ID NO: 119)
CDR-H3	GTRAYHY (SEQ ID NO: 112)	GTRAYHY (SEQ ID NO: 112)	ARGTRA (SEQ ID NO: 120)
CDR-L1	RASDNLYSNLA (SEQ ID NO: 113)	RASDNLYSNLA (SEQ ID NO: 113)	YSNLAWY (SEQ ID NO: 121)
CDR-L2	DATNLAD (SEQ ID NO: 114)	DATNLAD (SEQ ID NO: 114)	LLVYDATNLA (SEQ ID NO: 122)
CDR-L3	QHFWGTPLT (SEQ ID NO: 115)	QHFWGTPLT (SEQ ID NO: 115)	QHFWGTPL (SEQ ID NO: 123)
Murine VH	QVQLQQPGAELVKPGASVKLSCKASGYTFTSYWMHWVKQRPQGQGLEWIGEINPTNGRTNYIEKFKSKATLTVDKSSSTAYMQLSSLTSEDSAVYYCARGTRAYHYWGQGTSVTVSS (SEQ ID NO: 124)		

Murine VL	DIQMTQSPASLSVSVGETVTITCRASDNLYSNLAWYQQKQKSPQLLVYDATNL ADGVPSRFGSGSGGTQYSLKINSLQSEDFGTYYCQHFHWGTPLTFGAGTKLELK (SEQ ID NO: 125)
Humanized VH	EVQLVQSGAEVKKPGASVKVSCASGYTFTSYWMHWVRQAPGQRLEWIGEIN PTNGRTNYIEKFKSRATLTVDKSASTAYMELSSLRSEDTAVYYCARGTRAYHY WGQGTMTVTVSS (SEQ ID NO: 128)
Humanized VL	DIQMTQSPSSLSASVGDRVITITCRASDNLYSNLAWYQQKPGKSPKLLVYDATNL ADGVPSRFGSGSGGTDTLTISLQPEDFATYYCQHFHWGTPLTFGQGTKEIK (SEQ ID NO: 129)
HC of chimeric full-length IgG1	QVQLQQPGAELVKPGASVKLSCKASGYTFTSYWMHWVKRPGQGGLWIGEINP TNGRTNYIEKFKSKATLTVDKSSSTAYMQLSSLTSEDSAVYYCARGTRAYHYW GQGTSTVTSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSG ALTSGVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHKPSNTKVDKKVE PKSCDKTHTCPPCPAPELLGGPSVFLFPPKPKDTLMISRTPEVTCVVDVSHEDPE VKFNWYVDGVEVHNAKTKPREEQYNSTYRVVSVLTVLHQDWLNGKEYKCKV SNKALPAPIEKTISKAKGQPREPQVYTLPPSRDELTKNQVSLTCLVKGFYPSDIAV EWESNGQPENNYKTPPVLDSDGSFFLYSKLTVDKSRWQQGNVFCSCVMHEAL HNHYTQKSLSLSPGK (SEQ ID NO: 132)
LC of chimeric full-length IgG1	DIQMTQSPASLSVSVGETVTITCRASDNLYSNLAWYQQKQKSPQLLVYDATNL ADGVPSRFGSGSGGTQYSLKINSLQSEDFGTYYCQHFHWGTPLTFGAGTKLELKR TVAAPSVFIFPPSDEQLKSGTASVCLLNPFYPREAKVQWKVDNALQSGNSQES VTEQDSKDSYSLSSLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC (SEQ ID NO: 133)
HC of fully human full-length IgG1	EVQLVQSGAEVKKPGASVKVSCASGYTFTSYWMHWVRQAPGQRLEWIGEIN PTNGRTNYIEKFKSRATLTVDKSASTAYMELSSLRSEDTAVYYCARGTRAYHY WGQGTMTVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNS GALTSGVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHKPSNTKVDKKV EPKSCDKTHTCPPCPAPELLGGPSVFLFPPKPKDTLMISRTPEVTCVVDVSHEDP EVKFNWYVDGVEVHNAKTKPREEQYNSTYRVVSVLTVLHQDWLNGKEYKCK VSNKALPAPIEKTISKAKGQPREPQVYTLPPSRDELTKNQVSLTCLVKGFYPSDIA VEWESNGQPENNYKTPPVLDSDGSFFLYSKLTVDKSRWQQGNVFCSCVMHEA LHNHYTQKSLSLSPGK (SEQ ID NO: 134)
LC of fully human full-length IgG1	DIQMTQSPSSLSASVGDRVITITCRASDNLYSNLAWYQQKPGKSPKLLVYDATNL ADGVPSRFGSGSGGTDTLTISLQPEDFATYYCQHFHWGTPLTFGQGTKEIKRT VAAPSVFIFPPSDEQLKSGTASVCLLNPFYPREAKVQWKVDNALQSGNSQESV TEQDSKDSYSLSSLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC (SEQ ID NO: 135)
HC of chimeric Fab	QVQLQQPGAELVKPGASVKLSCKASGYTFTSYWMHWVKRPGQGGLWIGEINP TNGRTNYIEKFKSKATLTVDKSSSTAYMQLSSLTSEDSAVYYCARGTRAYHYW GQGTSTVTSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSG ALTSGVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHKPSNTKVDKKVE PKSCDKTHTCP (SEQ ID NO: 136)
HC of fully human Fab	EVQLVQSGAEVKKPGASVKVSCASGYTFTSYWMHWVRQAPGQRLEWIGEIN PTNGRTNYIEKFKSRATLTVDKSASTAYMELSSLRSEDTAVYYCARGTRAYHY WGQGTMTVTVSSASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNS GALTSGVHTFPAVLQSSGLYSLSSVTVPSSSLGTQTYICNVNHKPSNTKVDKKV EPKSCDKTHTCP (SEQ ID NO: 137)

[000146] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a CDR-H1, a CDR-H2, and a CDR-H3 that are the same as the CDR-H1, CDR-H2, and CDR-H3 shown in **Table 7**. Alternatively or in addition (e.g., in addition), the anti-TfR1 antibody of the present disclosure comprises a CDR-L1, a CDR-L2, and a CDR-L3 that are the same as the CDR-L1, CDR-L2, and CDR-L3 shown in **Table 7**.

[000147] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a CDR-L3, which contains no more than 3 amino acid variations (e.g., no more than 3, 2, or 1

amino acid variation) as compared with the CDR-L3 as shown in **Table 7**. In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a CDR-L3 containing one amino acid variation as compared with the CDR-L3 as shown in **Table 7**. In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a CDR-L3 of QHFAGTPLT (SEQ ID NO: 126) according to the Kabat and Chothia definition system) or QHFAGTPL (SEQ ID NO: 127) according to the Contact definition system). In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a CDR-H1, a CDR-H2, a CDR-H3, a CDR-L1 and a CDR-L2 that are the same as the CDR-H1, CDR-H2, and CDR-H3 shown in **Table 7**, and comprises a CDR-L3 of QHFAGTPLT (SEQ ID NO: 126) according to the Kabat and Chothia definition system) or QHFAGTPL (SEQ ID NO: 127) according to the Contact definition system).

[000148] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises heavy chain CDRs that collectively are at least 80% (e.g., 80%, 85%, 90%, 95%, or 98%) identical to the heavy chain CDRs as shown in **Table 7**. Alternatively or in addition (e.g., in addition), the anti-TfR1 antibody of the present disclosure comprises light chain CDRs that collectively are at least 80% (e.g., 80%, 85%, 90%, 95%, or 98%) identical to the light chain CDRs as shown in **Table 7**.

[000149] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VH comprising the amino acid sequence of SEQ ID NO: 124. Alternatively or in addition (e.g., in addition), the anti-TfR1 antibody of the present disclosure comprises a VL comprising the amino acid sequence of SEQ ID NO: 125.

[000150] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VH comprising the amino acid sequence of SEQ ID NO: 128. Alternatively or in addition (e.g., in addition), the anti-TfR1 antibody of the present disclosure comprises a VL comprising the amino acid sequence of SEQ ID NO: 129.

[000151] In some embodiments, the anti-TfR1 antibody of the present disclosure comprises a VH containing no more than 25 amino acid variations (e.g., no more than 25, 24, 23, 22, 21, 20, 19, 18, 17, 16, 15, 14, 13, 12, 11, 10, 9, 8, 7, 6, 5, 4, 3, 2, or 1 amino acid variation) as compared with the VH as set forth in SEQ ID NO: 128. Alternatively or in addition (e.g., in addition), the anti-TfR1 antibody of the present disclosure comprises a VL containing no more than 15 amino acid variations (e.g., no more than 20, 19, 18, 17, 16, 15, 14, 13, 12, 11, 9, 8, 7, 6, 5, 4, 3, 2, or 1 amino acid variation) as compared with the VL as set forth in SEQ ID NO: 129.

[000152] In some embodiments, the anti-TfR1 antibody of the present disclosure is a full-length IgG1 antibody, which can include a heavy constant region and a light constant region from a human antibody. In some embodiments, the heavy chain of any of the anti-TfR1

antibodies as described herein may comprises a heavy chain constant region (CH) or a portion thereof (e.g., CH1, CH2, CH3, or a combination thereof). The heavy chain constant region can of any suitable origin, e.g., human, mouse, rat, or rabbit. In one specific example, the heavy chain constant region is from a human IgG (a gamma heavy chain), e.g., IgG1, IgG2, or IgG4. An example of human IgG1 constant region is given below:

ASTKGPSVFPLAPSSKSTSGGTAALGCLVKDYFPEPVTVSWNSGALTSGVHTFPAVLQSSGLYSLSVVTVPSSSLGTQTYICNVNHKPSNTKVDKKVEPKSCDKTHTCPPCPAPELLGPSVFLFPPKPKDTLMISRTPEVTCVVVDVSHEDPEVKFNWYVDGVEVHNAKTKPREEQYNSTYRVVSVLTVLHQDWLNGKEYKCKVSNKALPAPIEKTISKAKGQPREPQVYTLPPSRDELTKNQVSLTCLVKGFYPSDIAVEWESNGQPENNYKTTTPVLDSDGSFFLYSKLTVDKSRWQQGNVFCFSVMHEALHNHYTQKSLSLSPGK (SEQ ID NO: 81)

[000153] In some embodiments, the light chain of any of the anti-TfR1 antibodies described herein may further comprise a light chain constant region (CL), which can be any CL known in the art. In some examples, the CL is a kappa light chain. In other examples, the CL is a lambda light chain. In some embodiments, the CL is a kappa light chain, the sequence of which is provided below:

RTVAAPSVFIFPPSDEQLKSGTASVVCLLNNFYPREAKVQWKVDNALQSGNSQESVTEQDSKDSTYLSSTLTLSKADYEKHKVYACEVTHQGLSSPVTKSFNRGEC (SEQ ID NO: 83)

[000154] In some embodiments, the anti-TfR1 antibody described herein is a chimeric antibody that comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 132. Alternatively or in addition (e.g., in addition), the anti-TfR1 antibody described herein comprises a light chain comprising the amino acid sequence of SEQ ID NO: 133.

[000155] In some embodiments, the anti-TfR1 antibody described herein is a fully human antibody that comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 134. Alternatively or in addition (e.g., in addition), the anti-TfR1 antibody described herein comprises a light chain comprising the amino acid sequence of SEQ ID NO: 135.

[000156] In some embodiments, the anti-TfR1 antibody is an antigen binding fragment (Fab) of an intact antibody (full-length antibody). In some embodiments, the anti-TfR1 Fab described herein comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 136. Alternatively or in addition (e.g., in addition), the anti-TfR1 Fab described herein comprises a light chain comprising the amino acid sequence of SEQ ID NO: 133. In some embodiments, the anti-TfR1 Fab described herein comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 137. Alternatively or in addition (e.g., in addition), the anti-TfR1 Fab described herein comprises a light chain comprising the amino acid sequence of SEQ ID NO: 135.

[000157] The anti-TfR1 antibodies described herein can be in any antibody form, including, but not limited to, intact (i.e., full-length) antibodies, antigen-binding fragments thereof (such as Fab, Fab', F(ab')₂, Fv), single chain antibodies, bi-specific antibodies, or nanobodies. In some embodiments, the anti-TfR1 antibody described herein is an scFv. In some embodiments, the anti-TfR1 antibody described herein is an scFv-Fab (e.g., scFv fused to a portion of a constant region). In some embodiments, the anti-TfR1 antibody described herein is an scFv fused to a constant region (e.g., human IgG1 constant region as set forth in SEQ ID NO: 81).

[000158] In some embodiments, conservative mutations can be introduced into antibody sequences (e.g., CDRs or framework sequences) at positions where the residues are not likely to be involved in interacting with a target antigen (e.g., transferrin receptor), for example, as determined based on a crystal structure. In some embodiments, one, two or more mutations (e.g., amino acid substitutions) are introduced into the Fc region of an anti-TfR1 antibody described herein (e.g., in a CH₂ domain (residues 231-340 of human IgG1) and/or (e.g., and) CH₃ domain (residues 341-447 of human IgG1) and/or (e.g., and) the hinge region, with numbering according to the Kabat numbering system (e.g., the EU index in Kabat)) to alter one or more functional properties of the antibody, such as serum half-life, complement fixation, Fc receptor binding and/or (e.g., and) antigen-dependent cellular cytotoxicity.

[000159] In some embodiments, one, two or more mutations (e.g., amino acid substitutions) are introduced into the hinge region of the Fc region (CH₁ domain) such that the number of cysteine residues in the hinge region are altered (e.g., increased or decreased) as described in, e.g., U.S. Pat. No. 5,677,425. The number of cysteine residues in the hinge region of the CH₁ domain can be altered to, e.g., facilitate assembly of the light and heavy chains, or to alter (e.g., increase or decrease) the stability of the antibody or to facilitate linker conjugation.

[000160] In some embodiments, one, two or more mutations (e.g., amino acid substitutions) are introduced into the Fc region of a muscle-targeting antibody described herein (e.g., in a CH₂ domain (residues 231-340 of human IgG1) and/or (e.g., and) CH₃ domain (residues 341-447 of human IgG1) and/or (e.g., and) the hinge region, with numbering according to the Kabat numbering system (e.g., the EU index in Kabat)) to increase or decrease the affinity of the antibody for an Fc receptor (e.g., an activated Fc receptor) on the surface of an effector cell. Mutations in the Fc region of an antibody that decrease or increase the affinity of an antibody for an Fc receptor and techniques for introducing such mutations into the Fc receptor or fragment thereof are known to one of skill in the art. Examples of mutations in the Fc receptor of an antibody that can be made to alter the affinity of the antibody for an Fc receptor are described in, e.g., Smith P et al., (2012) PNAS 109: 6181-6186, U.S. Pat. No. 6,737,056, and International

Publication Nos. WO 02/060919; WO 98/23289; and WO 97/34631, which are incorporated herein by reference.

[000161] In some embodiments, one, two or more amino acid mutations (*i.e.*, substitutions, insertions or deletions) are introduced into an IgG constant domain, or FcRn-binding fragment thereof (preferably an Fc or hinge-Fc domain fragment) to alter (*e.g.*, decrease or increase) half-life of the antibody *in vivo*. See, *e.g.*, International Publication Nos. WO 02/060919; WO 98/23289; and WO 97/34631; and U.S. Pat. Nos. 5,869,046, 6,121,022, 6,277,375 and 6,165,745 for examples of mutations that will alter (*e.g.*, decrease or increase) the half-life of an antibody *in vivo*.

[000162] In some embodiments, one, two or more amino acid mutations (*i.e.*, substitutions, insertions or deletions) are introduced into an IgG constant domain, or FcRn-binding fragment thereof (preferably an Fc or hinge-Fc domain fragment) to decrease the half-life of the anti-TfR1 antibody *in vivo*. In some embodiments, one, two or more amino acid mutations (*i.e.*, substitutions, insertions or deletions) are introduced into an IgG constant domain, or FcRn-binding fragment thereof (preferably an Fc or hinge-Fc domain fragment) to increase the half-life of the antibody *in vivo*. In some embodiments, the antibodies can have one or more amino acid mutations (*e.g.*, substitutions) in the second constant (CH2) domain (residues 231-340 of human IgG1) and/or (*e.g.*, and) the third constant (CH3) domain (residues 341-447 of human IgG1), with numbering according to the EU index in Kabat (Kabat E A et al., (1991) *supra*). In some embodiments, the constant region of the IgG1 of an antibody described herein comprises a methionine (M) to tyrosine (Y) substitution in position 252, a serine (S) to threonine (T) substitution in position 254, and a threonine (T) to glutamic acid (E) substitution in position 256, numbered according to the EU index as in Kabat. See U.S. Pat. No. 7,658,921, which is incorporated herein by reference. This type of mutant IgG, referred to as "YTE mutant" has been shown to display fourfold increased half-life as compared to wild-type versions of the same antibody (see Dall'Acqua W F et al., (2006) *J Biol Chem* 281: 23514-24). In some embodiments, an antibody comprises an IgG constant domain comprising one, two, three or more amino acid substitutions of amino acid residues at positions 251-257, 285-290, 308-314, 385-389, and 428-436, numbered according to the EU index as in Kabat.

[000163] In some embodiments, one, two or more amino acid substitutions are introduced into an IgG constant domain Fc region to alter the effector function(s) of the anti-TfR1 antibody. The effector ligand to which affinity is altered can be, for example, an Fc receptor or the C1 component of complement. This approach is described in further detail in U.S. Pat. Nos. 5,624,821 and 5,648,260. In some embodiments, the deletion or inactivation (through point mutations or other means) of a constant region domain can reduce Fc receptor binding of the

circulating antibody thereby increasing tumor localization. See, e.g., U.S. Pat. Nos. 5,585,097 and 8,591,886 for a description of mutations that delete or inactivate the constant domain and thereby increase tumor localization. In some embodiments, one or more amino acid substitutions may be introduced into the Fc region of an antibody described herein to remove potential glycosylation sites on Fc region, which may reduce Fc receptor binding (see, e.g., Shields R L et al., (2001) J Biol Chem 276: 6591-604).

[000164] In some embodiments, one or more amino in the constant region of an anti-TfR1 antibody described herein can be replaced with a different amino acid residue such that the antibody has altered C1q binding and/or (e.g., and) reduced or abolished complement dependent cytotoxicity (CDC). This approach is described in further detail in U.S. Pat. No. 6,194,551 (Idusogie et al). In some embodiments, one or more amino acid residues in the N-terminal region of the CH2 domain of an antibody described herein are altered to thereby alter the ability of the antibody to fix complement. This approach is described further in International Publication No. WO 94/29351. In some embodiments, the Fc region of an antibody described herein is modified to increase the ability of the antibody to mediate antibody dependent cellular cytotoxicity (ADCC) and/or (e.g., and) to increase the affinity of the antibody for an Fcγ receptor. This approach is described further in International Publication No. WO 00/42072.

[000165] In some embodiments, the heavy and/or (e.g., and) light chain variable domain(s) sequence(s) of the antibodies provided herein can be used to generate, for example, CDR-grafted, chimeric, humanized, or composite human antibodies or antigen-binding fragments, as described elsewhere herein. As understood by one of ordinary skill in the art, any variant, CDR-grafted, chimeric, humanized, or composite antibodies derived from any of the antibodies provided herein may be useful in the compositions and methods described herein and will maintain the ability to specifically bind transferrin receptor, such that the variant, CDR-grafted, chimeric, humanized, or composite antibody has at least 50%, at least 60%, at least 70%, at least 80%, at least 90%, at least 95% or more binding to transferrin receptor relative to the original antibody from which it is derived.

[000166] In some embodiments, the antibodies provided herein comprise mutations that confer desirable properties to the antibodies. For example, to avoid potential complications due to Fab-arm exchange, which is known to occur with native IgG4 mAbs, the antibodies provided herein may comprise a stabilizing 'Adair' mutation (Angal S., et al., "A single amino acid substitution abolishes the heterogeneity of chimeric mouse/human (IgG4) antibody," Mol Immunol 30, 105-108; 1993), where serine 228 (EU numbering; residue 241 Kabat numbering) is converted to proline resulting in an IgG1-like hinge sequence. Accordingly, any of the antibodies may include a stabilizing 'Adair' mutation.

[000167] In some embodiments, an antibody is modified, e.g., modified via glycosylation, phosphorylation, sumoylation, and/or (e.g., and) methylation. In some embodiments, an antibody is a glycosylated antibody, which is conjugated to one or more sugar or carbohydrate molecules. In some embodiments, the one or more sugar or carbohydrate molecule are conjugated to the antibody via N-glycosylation, O-glycosylation, C-glycosylation, glypiation (GPI anchor attachment), and/or (e.g., and) phosphoglycosylation. In some embodiments, the one or more sugar or carbohydrate molecules are monosaccharides, disaccharides, oligosaccharides, or glycans. In some embodiments, the one or more sugar or carbohydrate molecule is a branched oligosaccharide or a branched glycan. In some embodiments, the one or more sugar or carbohydrate molecule includes a mannose unit, a glucose unit, an N-acetylglucosamine unit, an N-acetylgalactosamine unit, a galactose unit, a fucose unit, or a phospholipid unit. In some embodiments, there are about 1-10, about 1-5, about 5-10, about 1-4, about 1-3, or about 2 sugar molecules. In some embodiments, a glycosylated antibody is fully or partially glycosylated. In some embodiments, an antibody is glycosylated by chemical reactions or by enzymatic means. In some embodiments, an antibody is glycosylated in vitro or inside a cell, which may optionally be deficient in an enzyme in the N- or O- glycosylation pathway, e.g., a glycosyltransferase. In some embodiments, an antibody is functionalized with sugar or carbohydrate molecules as described in International Patent Application Publication WO2014065661, published on May 1, 2014, entitled, “*Modified antibody, antibody-conjugate and process for the preparation thereof*”.

[000168] In some embodiments, any one of the anti-TfR1 antibodies described herein may comprise a signal peptide in the heavy and/or (e.g., and) light chain sequence (e.g., a N-terminal signal peptide). In some embodiments, the anti-TfR1 antibody described herein comprises any one of the VH and VL sequences, any one of the IgG heavy chain and light chain sequences, or any one of the F(ab') heavy chain and light chain sequences described herein, and further comprises a signal peptide (e.g., a N-terminal signal peptide). In some embodiments, the signal peptide comprises the amino acid sequence of MGWSCIILFLVATATGVHS (SEQ ID NO: 104).

In some embodiments, an antibody provided herein may have one or more post-translational modifications. In some embodiments, N-terminal cyclization, also called pyroglutamate formation (pyro-Glu), may occur in the antibody during production. In some embodiments, pyroglutamate formation occurs in the antibody at N-terminal Glutamate (Glu) and/or Glutamine (Gln) residues during production. As such, it should be appreciated that an antibody specified as having a sequence comprising an N-terminal glutamate or glutamine residue encompasses antibodies that have undergone pyroglutamate formation resulting from a post-translational

modification. In some embodiments, pyroglutamate formation occurs in a heavy chain sequence. In some embodiments, pyroglutamate formation occurs in a light chain sequence.

b. Other Muscle-Targeting Antibodies

[000169] In some embodiments, the muscle-targeting antibody is an antibody that specifically binds hemojuvelin, caveolin-3, Duchenne muscular dystrophy peptide, myosin IIb, or CD63. In some embodiments, the muscle-targeting antibody is an antibody that specifically binds a myogenic precursor protein. Exemplary myogenic precursor proteins include, without limitation, ABCG2, M-Cadherin/Cadherin-15, Caveolin-1, CD34, FoxK1, Integrin alpha 7, Integrin alpha 7 beta 1, MYF-5, MyoD, Myogenin, NCAM-1/CD56, Pax3, Pax7, and Pax9. In some embodiments, the muscle-targeting antibody is an antibody that specifically binds a skeletal muscle protein. Exemplary skeletal muscle proteins include, without limitation, alpha-Sarcoglycan, beta-Sarcoglycan, Calpain Inhibitors, Creatine Kinase MM/CKMM, eIF5A, Enolase 2/Neuron-specific Enolase, epsilon-Sarcoglycan, FABP3/H-FABP, GDF-8/Myostatin, GDF-11/GDF-8, Integrin alpha 7, Integrin alpha 7 beta 1, Integrin beta 1/CD29, MCAM/CD146, MyoD, Myogenin, Myosin Light Chain Kinase Inhibitors, NCAM-1/CD56, and Troponin I. In some embodiments, the muscle-targeting antibody is an antibody that specifically binds a smooth muscle protein. Exemplary smooth muscle proteins include, without limitation, alpha-Smooth Muscle Actin, VE-Cadherin, Caldesmon/CALD1, Calponin 1, Desmin, Histamine H2 R, Motilin R/GPR38, Transgelin/TAGLN, and Vimentin. However, it should be appreciated that antibodies to additional targets are within the scope of this disclosure and the exemplary lists of targets provided herein are not meant to be limiting.

c. Antibody Features/Alterations

[000170] In some embodiments, conservative mutations can be introduced into antibody sequences (e.g., CDRs or framework sequences) at positions where the residues are not likely to be involved in interacting with a target antigen (e.g., transferrin receptor), for example, as determined based on a crystal structure. In some embodiments, one, two or more mutations (e.g., amino acid substitutions) are introduced into the Fc region of a muscle-targeting antibody described herein (e.g., in a CH2 domain (residues 231-340 of human IgG1) and/or (e.g., and) CH3 domain (residues 341-447 of human IgG1) and/or (e.g., and) the hinge region, with numbering according to the Kabat numbering system (e.g., the EU index in Kabat)) to alter one or more functional properties of the antibody, such as serum half-life, complement fixation, Fc receptor binding and/or (e.g., and) antigen-dependent cellular cytotoxicity.

[000171] In some embodiments, one, two or more mutations (*e.g.*, amino acid substitutions) are introduced into the hinge region of the Fc region (CH1 domain) such that the number of cysteine residues in the hinge region are altered (*e.g.*, increased or decreased) as described in, *e.g.*, U.S. Pat. No. 5,677,425. The number of cysteine residues in the hinge region of the CH1 domain can be altered to, *e.g.*, facilitate assembly of the light and heavy chains, or to alter (*e.g.*, increase or decrease) the stability of the antibody or to facilitate linker conjugation.

[000172] In some embodiments, one, two or more mutations (*e.g.*, amino acid substitutions) are introduced into the Fc region of a muscle-targeting antibody described herein (*e.g.*, in a CH2 domain (residues 231-340 of human IgG1) and/or (*e.g.*, and) CH3 domain (residues 341-447 of human IgG1) and/or (*e.g.*, and) the hinge region, with numbering according to the Kabat numbering system (*e.g.*, the EU index in Kabat)) to increase or decrease the affinity of the antibody for an Fc receptor (*e.g.*, an activated Fc receptor) on the surface of an effector cell. Mutations in the Fc region of an antibody that decrease or increase the affinity of an antibody for an Fc receptor and techniques for introducing such mutations into the Fc receptor or fragment thereof are known to one of skill in the art. Examples of mutations in the Fc receptor of an antibody that can be made to alter the affinity of the antibody for an Fc receptor are described in, *e.g.*, Smith P et al., (2012) PNAS 109: 6181-6186, U.S. Pat. No. 6,737,056, and International Publication Nos. WO 02/060919; WO 98/23289; and WO 97/34631, which are incorporated herein by reference.

[000173] In some embodiments, one, two or more amino acid mutations (*i.e.*, substitutions, insertions or deletions) are introduced into an IgG constant domain, or FcRn-binding fragment thereof (preferably an Fc or hinge-Fc domain fragment) to alter (*e.g.*, decrease or increase) half-life of the antibody *in vivo*. See, *e.g.*, International Publication Nos. WO 02/060919; WO 98/23289; and WO 97/34631; and U.S. Pat. Nos. 5,869,046, 6,121,022, 6,277,375 and 6,165,745 for examples of mutations that will alter (*e.g.*, decrease or increase) the half-life of an antibody *in vivo*.

[000174] In some embodiments, one, two or more amino acid mutations (*i.e.*, substitutions, insertions or deletions) are introduced into an IgG constant domain, or FcRn-binding fragment thereof (preferably an Fc or hinge-Fc domain fragment) to decrease the half-life of the anti-transferrin receptor antibody *in vivo*. In some embodiments, one, two or more amino acid mutations (*i.e.*, substitutions, insertions or deletions) are introduced into an IgG constant domain, or FcRn-binding fragment thereof (preferably an Fc or hinge-Fc domain fragment) to increase the half-life of the antibody *in vivo*. In some embodiments, the antibodies can have one or more amino acid mutations (*e.g.*, substitutions) in the second constant (CH2) domain (residues 231-340 of human IgG1) and/or (*e.g.*, and) the third constant (CH3) domain (residues

341-447 of human IgG1), with numbering according to the EU index in Kabat (Kabat E A et al., (1991) *supra*). In some embodiments, the constant region of the IgG1 of an antibody described herein comprises a methionine (M) to tyrosine (Y) substitution in position 252, a serine (S) to threonine (T) substitution in position 254, and a threonine (T) to glutamic acid (E) substitution in position 256, numbered according to the EU index as in Kabat. See U.S. Pat. No. 7,658,921, which is incorporated herein by reference. This type of mutant IgG, referred to as "YTE mutant" has been shown to display fourfold increased half-life as compared to wild-type versions of the same antibody (see Dall'Acqua W F et al., (2006) *J Biol Chem* 281: 23514-24). In some embodiments, an antibody comprises an IgG constant domain comprising one, two, three or more amino acid substitutions of amino acid residues at positions 251-257, 285-290, 308-314, 385-389, and 428-436, numbered according to the EU index as in Kabat.

[000175] In some embodiments, one, two or more amino acid substitutions are introduced into an IgG constant domain Fc region to alter the effector function(s) of the anti-transferrin receptor antibody. The effector ligand to which affinity is altered can be, for example, an Fc receptor or the C1 component of complement. This approach is described in further detail in U.S. Pat. Nos. 5,624,821 and 5,648,260. In some embodiments, the deletion or inactivation (through point mutations or other means) of a constant region domain can reduce Fc receptor binding of the circulating antibody thereby increasing tumor localization. See, e.g., U.S. Pat. Nos. 5,585,097 and 8,591,886 for a description of mutations that delete or inactivate the constant domain and thereby increase tumor localization. In some embodiments, one or more amino acid substitutions may be introduced into the Fc region of an antibody described herein to remove potential glycosylation sites on Fc region, which may reduce Fc receptor binding (see, e.g., Shields R L et al., (2001) *J Biol Chem* 276: 6591-604).

[000176] In some embodiments, one or more amino in the constant region of a muscle-targeting antibody described herein can be replaced with a different amino acid residue such that the antibody has altered C1q binding and/or (e.g., and) reduced or abolished complement dependent cytotoxicity (CDC). This approach is described in further detail in U.S. Pat. No. 6,194,551 (Idusogie et al). In some embodiments, one or more amino acid residues in the N-terminal region of the CH2 domain of an antibody described herein are altered to thereby alter the ability of the antibody to fix complement. This approach is described further in International Publication No. WO 94/29351. In some embodiments, the Fc region of an antibody described herein is modified to increase the ability of the antibody to mediate antibody dependent cellular cytotoxicity (ADCC) and/or (e.g., and) to increase the affinity of the antibody for an Fcγ receptor. This approach is described further in International Publication No. WO 00/42072.

[000177] In some embodiments, the heavy and/or (e.g., and) light chain variable domain(s) sequence(s) of the antibodies provided herein can be used to generate, for example, CDR-grafted, chimeric, humanized, or composite human antibodies or antigen-binding fragments, as described elsewhere herein. As understood by one of ordinary skill in the art, any variant, CDR-grafted, chimeric, humanized, or composite antibodies derived from any of the antibodies provided herein may be useful in the compositions and methods described herein and will maintain the ability to specifically bind transferrin receptor, such that the variant, CDR-grafted, chimeric, humanized, or composite antibody has at least 50%, at least 60%, at least 70%, at least 80%, at least 90%, at least 95% or more binding to transferrin receptor relative to the original antibody from which it is derived.

[000178] In some embodiments, the antibodies provided herein comprise mutations that confer desirable properties to the antibodies. For example, to avoid potential complications due to Fab-arm exchange, which is known to occur with native IgG4 mAbs, the antibodies provided herein may comprise a stabilizing ‘Adair’ mutation (Angal S., et al., “A single amino acid substitution abolishes the heterogeneity of chimeric mouse/human (IgG4) antibody,” *Mol Immunol* 30, 105-108; 1993), where serine 228 (EU numbering; residue 241 Kabat numbering) is converted to proline resulting in an IgG1-like hinge sequence. Accordingly, any of the antibodies may include a stabilizing ‘Adair’ mutation.

[000179] As provided herein, antibodies of this disclosure may optionally comprise constant regions or parts thereof. For example, a VL domain may be attached at its C-terminal end to a light chain constant domain like C κ or C λ . Similarly, a VH domain or portion thereof may be attached to all or part of a heavy chain like IgA, IgD, IgE, IgG, and IgM, and any isotype subclass. Antibodies may include suitable constant regions (see, for example, Kabat et al., *Sequences of Proteins of Immunological Interest*, No. 91-3242, National Institutes of Health Publications, Bethesda, Md. (1991)). Therefore, antibodies within the scope of this may disclosure include VH and VL domains, or an antigen binding portion thereof, combined with any suitable constant regions.

ii. Muscle-Targeting Peptides

[000180] Some aspects of the disclosure provide muscle-targeting peptides as muscle-targeting agents. Short peptide sequences (e.g., peptide sequences of 5-20 amino acids in length) that bind to specific cell types have been described. For example, cell-targeting peptides have been described in Vines e., et al., A. “Cell-penetrating and cell-targeting peptides in drug delivery” *Biochim Biophys Acta* 2008, 1786: 126-38; Jarver P., et al., “In vivo biodistribution and efficacy of peptide mediated delivery” *Trends Pharmacol Sci* 2010; 31: 528-35; Samoylova

T.I., et al., “Elucidation of muscle-binding peptides by phage display screening” *Muscle Nerve* 1999; 22: 460-6; U.S. Patent No. 6,329,501, issued on December 11, 2001, entitled “METHODS AND COMPOSITIONS FOR TARGETING COMPOUNDS TO MUSCLE”; and Samoylov A.M., et al., “Recognition of cell-specific binding of phage display derived peptides using an acoustic wave sensor.” *Biomol Eng* 2002; 18: 269-72; the entire contents of each of which are incorporated herein by reference. By designing peptides to interact with specific cell surface antigens (e.g., receptors), selectivity for a desired tissue, e.g., muscle, can be achieved. Skeletal muscle-targeting has been investigated and a range of molecular payloads are able to be delivered. These approaches may have high selectivity for muscle tissue without many of the practical disadvantages of a large antibody or viral particle. Accordingly, in some embodiments, the muscle-targeting agent is a muscle-targeting peptide that is from 4 to 50 amino acids in length. In some embodiments, the muscle-targeting peptide is 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, or 50 amino acids in length. Muscle-targeting peptides can be generated using any of several methods, such as phage display.

[000181] In some embodiments, a muscle-targeting peptide may bind to an internalizing cell surface receptor that is overexpressed or relatively highly expressed in muscle cells, e.g., a transferrin receptor, compared with certain other cells. In some embodiments, a muscle-targeting peptide may target, e.g., bind to, a transferrin receptor. In some embodiments, a peptide that targets a transferrin receptor may comprise a segment of a naturally occurring ligand, e.g., transferrin. In some embodiments, a peptide that targets a transferrin receptor is as described in US Patent No. 6,743,893, filed 11/30/2000, “RECEPTOR-MEDIATED UPTAKE OF PEPTIDES THAT BIND THE HUMAN TRANSFERRIN RECEPTOR”. In some embodiments, a peptide that targets a transferrin receptor is as described in Kawamoto, M. et al, “A novel transferrin receptor-targeted hybrid peptide disintegrates cancer cell membrane to induce rapid killing of cancer cells.” *BMC Cancer*. 2011 Aug 18;11:359. In some embodiments, a peptide that targets a transferrin receptor is as described in US Patent No. 8,399,653, filed 5/20/2011, “TRANSFERRIN/TRANSFERRIN RECEPTOR-MEDIATED SIRNA DELIVERY”.

[000182] As discussed above, examples of muscle targeting peptides have been reported. For example, muscle-specific peptides were identified using phage display library presenting surface heptapeptides. As one example a peptide having the amino acid sequence ASSLNIA (SEQ ID NO: 130) bound to C2C12 murine myotubes *in vitro*, and bound to mouse muscle tissue *in vivo*. Accordingly, in some embodiments, the muscle-targeting agent comprises the amino acid sequence ASSLNIA (SEQ ID NO: 130). This peptide displayed improved

specificity for binding to heart and skeletal muscle tissue after intravenous injection in mice with reduced binding to liver, kidney, and brain. Additional muscle-specific peptides have been identified using phage display. For example, a 12 amino acid peptide was identified by phage display library for muscle targeting in the context of treatment for DMD. See, Yoshida D., et al., "Targeting of salicylate to skin and muscle following topical injections in rats." *Int J Pharm* 2002; 231: 177-84; the entire contents of which are hereby incorporated by reference. Here, a 12 amino acid peptide having the sequence SKTFNTHPQSTP (SEQ ID NO: 131) was identified and this muscle-targeting peptide showed improved binding to C2C12 cells relative to the ASSLNIA (SEQ ID NO: 130) peptide.

[000183] An additional method for identifying peptides selective for muscle (e.g., skeletal muscle) over other cell types includes *in vitro* selection, which has been described in Ghosh D., et al., "Selection of muscle-binding peptides from context-specific peptide-presenting phage libraries for adenoviral vector targeting" *J Virol* 2005; 79: 13667-72; the entire contents of which are incorporated herein by reference. By pre-incubating a random 12-mer peptide phage display library with a mixture of non-muscle cell types, non-specific cell binders were selected out. Following rounds of selection the 12 amino acid peptide TARGEHKEEELI (SEQ ID NO: 189) appeared most frequently. Accordingly, in some embodiments, the muscle-targeting agent comprises the amino acid sequence TARGEHKEEELI (SEQ ID NO: 189).

[000184] A muscle-targeting agent may be an amino acid-containing molecule or peptide. A muscle-targeting peptide may correspond to a sequence of a protein that preferentially binds to a protein receptor found in muscle cells. In some embodiments, a muscle-targeting peptide contains a high propensity of hydrophobic amino acids, e.g., valine, such that the peptide preferentially targets muscle cells. In some embodiments, a muscle-targeting peptide has not been previously characterized or disclosed. These peptides may be conceived of, produced, synthesized, and/or (e.g., and) derivatized using any of several methodologies, e.g., phage displayed peptide libraries, one-bead one-compound peptide libraries, or positional scanning synthetic peptide combinatorial libraries. Exemplary methodologies have been characterized in the art and are incorporated by reference (Gray, B.P. and Brown, K.C. "Combinatorial Peptide Libraries: Mining for Cell-Binding Peptides" *Chem Rev.* 2014, 114:2, 1020–1081.; Samoylova, T.I. and Smith, B.F. "Elucidation of muscle-binding peptides by phage display screening." *Muscle Nerve*, 1999, 22:4. 460-6.). In some embodiments, a muscle-targeting peptide has been previously disclosed (see, e.g., Writer M.J. et al. "Targeted gene delivery to human airway epithelial cells with synthetic vectors incorporating novel targeting peptides selected by phage display." *J. Drug Targeting*. 2004;12:185; Cai, D. "BDNF-mediated enhancement of inflammation and injury in the aging heart." *Physiol Genomics*. 2006, 24:3, 191-7.; Zhang, L.

“Molecular profiling of heart endothelial cells.” *Circulation*, 2005, 112:11, 1601-11.; McGuire, M.J. et al. “In vitro selection of a peptide with high selectivity for cardiomyocytes in vivo.” *J Mol Biol.* 2004, 342:1, 171-82.). Exemplary muscle-targeting peptides comprise an amino acid sequence of the following group: CQAQGQLVC (SEQ ID NO: 201), CSERSMNFC (SEQ ID NO: 202), CPKTRRVPC (SEQ ID NO: 203), WLSEAGPVVTVRALRGTGSW (SEQ ID NO: 204), ASSLNIA (SEQ ID NO: 130), CMQHSMRVC (SEQ ID NO: 205), and DDTRHWG (SEQ ID NO: 206). In some embodiments, a muscle-targeting peptide may comprise about 2-25 amino acids, about 2-20 amino acids, about 2-15 amino acids, about 2-10 amino acids, or about 2-5 amino acids. Muscle-targeting peptides may comprise naturally occurring amino acids, e.g., cysteine, alanine, or non-naturally occurring or modified amino acids. Non-naturally occurring amino acids include β -amino acids, homo-amino acids, proline derivatives, 3-substituted alanine derivatives, linear core amino acids, N-methyl amino acids, and others known in the art. In some embodiments, a muscle-targeting peptide may be linear; in other embodiments, a muscle-targeting peptide may be cyclic, e.g., bicyclic (see, e.g., Silvana, M.G. et al. *Mol. Therapy*, 2018, 26:1, 132–147.).

iii. Muscle-Targeting Receptor Ligands

[000185] A muscle-targeting agent may be a ligand, e.g., a ligand that binds to a receptor protein. A muscle-targeting ligand may be a protein, e.g., transferrin, which binds to an internalizing cell surface receptor expressed by a muscle cell. Accordingly, in some embodiments, the muscle-targeting agent is transferrin, or a derivative thereof that binds to a transferrin receptor. A muscle-targeting ligand may alternatively be a small molecule, e.g., a lipophilic small molecule that preferentially targets muscle cells relative to other cell types. Exemplary lipophilic small molecules that may target muscle cells include compounds comprising cholesterol, cholesteryl, stearic acid, palmitic acid, oleic acid, oleyl, linolene, linoleic acid, myristic acid, sterols, dihydrotestosterone, testosterone derivatives, glycerine, alkyl chains, trityl groups, and alkoxy acids.

iv. Muscle-Targeting Aptamers

[000186] A muscle-targeting agent may be an aptamer, e.g., an RNA aptamer, which preferentially targets muscle cells relative to other cell types. In some embodiments, a muscle-targeting aptamer has not been previously characterized or disclosed. These aptamers may be conceived of, produced, synthesized, and/or (e.g., and) derivatized using any of several methodologies, e.g., Systematic Evolution of Ligands by Exponential Enrichment. Exemplary methodologies have been characterized in the art and are incorporated by reference (Yan, A.C. and Levy, M. “Aptamers and aptamer targeted delivery” *RNA biology*, 2009, 6:3, 316-20.;

Germer, K. et al. "RNA aptamers and their therapeutic and diagnostic applications." *Int. J. Biochem. Mol. Biol.* 2013; 4: 27–40.). In some embodiments, a muscle-targeting aptamer has been previously disclosed (see, e.g., Phillippou, S. et al. "Selection and Identification of Skeletal-Muscle-Targeted RNA Aptamers." *Mol Ther Nucleic Acids*. 2018, 10:199-214.; Thiel, W.H. et al. "Smooth Muscle Cell-targeted RNA Aptamer Inhibits Neointimal Formation." *Mol Ther*. 2016, 24:4, 779-87.). Exemplary muscle-targeting aptamers include the A01B RNA aptamer and RNA Apt 14. In some embodiments, an aptamer is a nucleic acid-based aptamer, an oligonucleotide aptamer or a peptide aptamer. In some embodiments, an aptamer may be about 5-15 kDa, about 5-10 kDa, about 10-15 kDa, about 1-5 Da, about 1-3 kDa, or smaller.

v. Other Muscle-Targeting Agents

[000187] One strategy for targeting a muscle cell (e.g., a skeletal muscle cell) is to use a substrate of a muscle transporter protein, such as a transporter protein expressed on the sarcolemma. In some embodiments, the muscle-targeting agent is a substrate of an influx transporter that is specific to muscle tissue. In some embodiments, the influx transporter is specific to skeletal muscle tissue. Two main classes of transporters are expressed on the skeletal muscle sarcolemma, (1) the adenosine triphosphate (ATP) binding cassette (ABC) superfamily, which facilitate efflux from skeletal muscle tissue and (2) the solute carrier (SLC) superfamily, which can facilitate the influx of substrates into skeletal muscle. In some embodiments, the muscle-targeting agent is a substrate that binds to an ABC superfamily or an SLC superfamily of transporters. In some embodiments, the substrate that binds to the ABC or SLC superfamily of transporters is a naturally occurring substrate. In some embodiments, the substrate that binds to the ABC or SLC superfamily of transporters is a non-naturally occurring substrate, for example, a synthetic derivative thereof that binds to the ABC or SLC superfamily of transporters.

[000188] In some embodiments, the muscle-targeting agent is any muscle targeting agent described herein (e.g., antibodies, nucleic acids, small molecules, peptides, aptamers, lipids, sugar moieties) that target SLC superfamily of transporters. In some embodiments, the muscle-targeting agent is a substrate of an SLC superfamily of transporters. SLC transporters are either equilibrative or use proton or sodium ion gradients created across the membrane to drive transport of substrates. Exemplary SLC transporters that have high skeletal muscle expression include, without limitation, the SATT transporter (ASCT1; SLC1A4), GLUT4 transporter (SLC2A4), GLUT7 transporter (GLUT7; SLC2A7), ATRC2 transporter (CAT-2; SLC7A2), LAT3 transporter (KIAA0245; SLC7A6), PHT1 transporter (PTR4; SLC15A4), OATP-J transporter (OATP5A1; SLC21A15), OCT3 transporter (EMT; SLC22A3), OCTN2 transporter (FLJ46769; SLC22A5), ENT transporters (ENT1; SLC29A1 and ENT2; SLC29A2), PAT2

transporter (SLC36A2), and SAT2 transporter (KIAA1382; SLC38A2). These transporters can facilitate the influx of substrates into skeletal muscle, providing opportunities for muscle targeting.

[000189] In some embodiments, the muscle-targeting agent is a substrate of an equilibrative nucleoside transporter 2 (ENT2) transporter. Relative to other transporters, ENT2 has one of the highest mRNA expressions in skeletal muscle. While human ENT2 (hENT2) is expressed in most body organs such as brain, heart, placenta, thymus, pancreas, prostate, and kidney, it is especially abundant in skeletal muscle. Human ENT2 facilitates the uptake of its substrates depending on their concentration gradient. ENT2 plays a role in maintaining nucleoside homeostasis by transporting a wide range of purine and pyrimidine nucleobases. The hENT2 transporter has a low affinity for all nucleosides (adenosine, guanosine, uridine, thymidine, and cytidine) except for inosine. Accordingly, in some embodiments, the muscle-targeting agent is an ENT2 substrate. Exemplary ENT2 substrates include, without limitation, inosine, 2',3'-dideoxyinosine, and calofarabine. In some embodiments, any of the muscle-targeting agents provided herein are associated with a molecular payload (e.g., oligonucleotide payload). In some embodiments, the muscle-targeting agent is covalently linked to the molecular payload. In some embodiments, the muscle-targeting agent is non-covalently linked to the molecular payload.

[000190] In some embodiments, the muscle-targeting agent is a substrate of an organic cation/carnitine transporter (OCTN2), which is a sodium ion-dependent, high affinity carnitine transporter. In some embodiments, the muscle-targeting agent is carnitine, mildronate, acetylcarnitine, or any derivative thereof that binds to OCTN2. In some embodiments, the carnitine, mildronate, acetylcarnitine, or derivative thereof is covalently linked to the molecular payload (e.g., oligonucleotide payload).

[000191] A muscle-targeting agent may be a protein that is protein that exists in at least one soluble form that targets muscle cells. In some embodiments, a muscle-targeting protein may be hemojuvelin (also known as repulsive guidance molecule C or hemochromatosis type 2 protein), a protein involved in iron overload and homeostasis. In some embodiments, hemojuvelin may be full length or a fragment, or a mutant with at least 75%, at least 80%, at least 85%, at least 90%, at least 95%, at least 98% or at least 99% sequence identity to a functional hemojuvelin protein. In some embodiments, a hemojuvelin mutant may be a soluble fragment, may lack a N-terminal signaling, and/or (e.g., and) lack a C-terminal anchoring domain. In some embodiments, hemojuvelin may be annotated under GenBank RefSeq Accession Numbers NM_001316767.1, NM_145277.4, NM_202004.3, NM_213652.3, or

NM_213653.3. It should be appreciated that a hemojuvelin may be of human, non-human primate, or rodent origin.

B. Molecular Payloads

[000192] Some aspects of the disclosure provide molecular payloads, e.g., for modulating a biological outcome, e.g., the transcription of a DNA sequence, the expression of a protein, or the activity of a protein. In some embodiments, a molecular payload is covalently linked to, or otherwise associated with a molecular payloads. In some embodiments, such molecular payloads are capable of targeting to a muscle cell, e.g., via specifically binding to a nucleic acid or protein in the muscle cell following delivery to the muscle cell by an associated muscle-targeting agent. It should be appreciated that various types of muscle-targeting agents may be used in accordance with the disclosure. For example, the molecular payload may comprise, or consist of, an oligonucleotide (e.g., antisense oligonucleotide), a peptide (e.g., a peptide that binds a nucleic acid or protein associated with disease in a muscle cell), a protein (e.g., a protein that binds a nucleic acid or protein associated with disease in a muscle cell), or a small molecule (e.g., a small molecule that modulates the function of a nucleic acid or protein associated with disease in a muscle cell). In some embodiments, the molecular payload is an oligonucleotide that comprises a strand having a region of complementarity to FXN (e.g., a GAA repeat). Exemplary molecular payloads are described in further detail herein, however, it should be appreciated that the exemplary molecular payloads provided herein are not meant to be limiting.

i. Oligonucleotides

[000193] Any suitable oligonucleotide may be used as a molecular payload, as described herein. In some embodiments, the oligonucleotide may be designed to cause degradation of an mRNA (e.g., the oligonucleotide may be a gapmer, an siRNA, a ribozyme or an aptamer that causes degradation). In some embodiments, the oligonucleotide may be designed to block translation of an mRNA (e.g., the oligonucleotide may be a mixmer, an siRNA or an aptamer that blocks translation). In some embodiments, the oligonucleotide may be designed to block formation of R-loop between the FXN RNA containing the expanded GAA repeat and chromosomal DNA. In some embodiments, the oligonucleotide is complementary to FXN RNA and are useful for increasing levels of functional FXN by blocking FXN RNA containing expanded GAA repeats, e.g., in a subject having or suspected of having Friedreich's ataxia. In some embodiments, an oligonucleotide may be designed to caused degradation and block translation of an mRNA. In some embodiments, an oligonucleotide may be a guide nucleic acid (e.g., guide RNA) for directing activity of an enzyme (e.g., a gene editing enzyme). Other

examples of oligonucleotides are provided herein. It should be appreciated that, in some embodiments, oligonucleotides in one format (e.g., antisense oligonucleotides) may be suitably adapted to another format (e.g., siRNA oligonucleotides) by incorporating functional sequences (e.g., antisense strand sequences) from one format to the other format.

[000194] Examples of oligonucleotides useful for targeting FXN and/or otherwise compensating for frataxin deficiency are provided in Li, L. et al “Activating frataxin expression by repeat-targeted nucleic acids” Nat. Comm. 2016, 7:10606.; WO 2016/094374, published 6/16/2016, “Compositions and methods for treatment of Friedreich's ataxia.”; WO 2015/020993, published 2/12/2015, “RNAi COMPOSITIONS AND METHODS FOR TREATMENT OF FRIEDREICH'S ATAXIA”; WO 2017/186815, published 11/2/2017, “Antisense oligonucleotides for enhanced expression of frataxin”; WO 2008/018795, published 2/14/2008, “Methods and means for treating DNA repeat instability associated genetic disorders”; US Patent Application 2018/0028557, published 2/1/2018, “Hybrid oligonucleotides and uses thereof”; WO 2015/023975, published 2/19/2015, “Compositions and methods for modulating RNA”; WO 2015/023939, published 2/19/2015, “Compositions and methods for modulating expression of frataxin”; US Patent Application 2017/0281643, published 10/5/2017, “Compounds and methods for modulating frataxin expression”; Li L. et al., “Activating frataxin expression by repeat-targeted nucleic acids” Nature Communications, Published 4 Feb 2016; and Li L. et al. “Activation of Frataxin Protein Expression by Antisense Oligonucleotides Targeting the Mutant Expanded Repeat” Nucleic Acid Ther. 2018 Feb;28(1):23-33., the contents of each of which are incorporated herein in their entireties.

[000195] In some embodiments, an oligonucleotide payload is configured (e.g., as a gapmer or RNAi oligonucleotide) for inhibiting expression of a natural antisense transcript that inhibits FXN expression, e.g., as disclosed in US Patent No. 9,593,330, filed 6/9/2011, “Treatment of frataxin (FXN) related diseases by inhibition of natural antisense transcript to FXN”, the contents of which are incorporated herein by reference in its entirety.

[000196] Examples of oligonucleotides for promoting FXN gene editing include WO 2016/094845, published 6/16/2016, “Compositions and methods for editing nucleic acids in cells utilizing oligonucleotides”; WO 2015/089354, published 6/18/2015, “Compositions and methods of use of CRISPR-Cas systems in nucleotide repeat disorders”; WO 2015/139139, published 9/24/2015, “CRISPR-based methods and products for increasing frataxin levels and uses thereof”; and WO 2018/002783, published 1/4/2018, “Materials and methods for treatment of Friedreich's ataxia and other related disorders”, the contents of each of which are incorporated herein in their entireties.

[000197] Examples of oligonucleotides for promoting FXN gene expression through targeting of non-FXN genes, *e.g.*, epigenetic regulators of FXN, include WO 2015/023938, published 2/19/2015, “Epigenetic regulators of frataxin”, the contents of which are incorporated herein in its entirety.

[000198] In some embodiments, oligonucleotides may have a region of complementarity to a sequence set forth as: a FXN gene from humans (Gene ID 2395; NC_000009.12) and/or a FXN gene from mice (Gene ID 14297; NC_000085.6). In some embodiments, the oligonucleotide may have region of complementarity to a mutant form of FXN, for example as reported in *e.g.*, Montermini, L. et al. “The Friedreich’s ataxia GAA triplet repeat: premutation and normal alleles.” *Hum. Molec. Genet.*, 1997, 6: 1261-1266.; Filla, A. et al. “The relationship between trinucleotide (GAA) repeat length and clinical features in Friedreich’s ataxia.” *Am. J. Hum. Genet.* 1996, 59: 554-560.; Pandolfo, M. Friedreich’s ataxia: the clinical picture. *J. Neurol.* 2009, 256, 3–8.; the contents of each of which are incorporated herein by reference in their entireties.

[000199] An example human FXN gene nucleotide sequence, corresponding to Gene ID 2395; NM_000144.5 is as follows:

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AGGGCGGAGCGGGCGGCAGACCCGGAGCAGCATGTGGACTCTCGGGCGCCGCGCAGTAGCCGGCCTC
CTGGCGTCACCCAGCCCAGCCCAGGCCAGACCCTACCCGGGTCCCGCGGCCGCGCAGAGTTGGCCC
CACTCTGCGGCCGCGCGTGGCCTGCGCACCGACATCGATGCGACCTGCACGCCCCGCGCGCAAGTTCG
AACCAACGTGGCCTCAACCAGATTTGGAATGTCAAAAAGCAGAGTGTCTATTTGATGAATTTGAGGA
AATCTGGAAC TTTGGGCCACCCAGGCTCTCTAGATGAGACCACCTATGAAAGACTAGCAGAGGAAAC
GCTGGACTCTTTAGCAGAGT TTTTGAAGACCTTG CAGACAAGCCATACACGTTTGAGGACTATGATG
TCTCCTTTGGGAGTGGTGTCTTA ACTGTCAA ACTGGGTGGAGATCTAGGAACCTATGTGATCAACAAG
CAGACGCCAAACAAGCAAATCTGGCTATCTTCTCCATCCAGTGGACCTAAGCGTTATGACTGGACTGG
GAAAAA CTGGGTGTACTCCACGACGGCGTGTCCCTCCATGAGCTGCTGGCCGCAGAGCTCACTAAA
GCCTTAAAAACCAA ACTGGACTTGTCTTCTTGGCCTATTCCGGA AAAAGATGCTTGATGCCCAGCCCC
GTTTTAAGGACATTAAAAAGCTATCAGGCCAAGACCCAGCTTCATTATGCAGCTGAGGTCTGTTTTTT
GTTGTTGTTGTTGTTTATTTTTTTTATTCCTGCTTTTGAGGACAGTTGGGCTATGTGTCACAGCTCTGTA
GAAAGAATGTGTTGCCCTCTACCTTGCCCCAAGTTCTGATTTTAAATTTCTATGGAAGATTTTTTGA
TTGTCGGATTTCTCTCCCTCACATGATACCCCTTATCTTTTATAATGTCTTATGCCTATACCTGAATATAA
CAACCTTTAAAAAAGCAAATAATAAGAAGGAAAAATCCAGGAGGGAAAAATGAATTGTCTTCACTC
TTCATCTTTGAAGGATTTACTGCAAGAAGTACATGAAGAGCAGCTGGTCAACCTGCTCACTGTTCTA
TCTCCAAATGAGACACATTAAAGGGTAGCCTACAAATGTTTTTCAGGCTTCTTTCAAAGTGTAAGCACT
TCTGAGCTCTTTAGCATTGAAGTGTGAAAGCAACTCACACGGGAAGATCATTTCTTATTTGTGCTCTG
TGACTGCCAAGGTGTGGCCTGCACTGGGTTGTCCAGGGAGACCTAGTGCTGTTTCTCCACATATTCA
CATACGTGTCTGTGTGTATATATATTTTTTCAATTTAAAGGTTAGTATGGAATCAGCTGCTACAAGAAT
GCAAAAAATCTTCAAAGACAAGAAAAGAGGAAAAAAGCCGTTTTTCATGAGCTGAGTGATGTAGCG
TAACAAACAAAATCATGGAGCTGAGGAGGTGCCTTGTAACATGAAGGGGCAGATAAAGGAAGGAG
ATACTCATGTTGATAAAGAGAGCCCTGGTCCTAGACATAGTTCAGCCACAAAGTAGTTGTCCCTTTGT
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GGACAAGTTTCCCAAATTCCCTGGACCTCTGCTTCCCCATCTGTAAATGAGAGAATAGAGTATGGTT
GATTCCCAGCATTTCAGTGGTCCTGTCAAGCAACCTAACAGGCTAGTTCTAATTCCTATTGGGTAGAT
GAGGGGATGACAAAGAACAGTTTTTAAAGCTATATAGGAAACATTGTTATTGGTGTGCCCCTATCGTGA
TTTCAGTTGAATTCATGTGAAAATAATAGCCATCCTTGGCCTGGCGCGGTGGCTCACACCTGTAATCC
CAGCACTTTTGGAGGCCAAGGTGGGTGGATCACCTGAGGTCAGGAGTTCAAGACCAGCCTGGCCAAC
ATGATGAAACCCCGTCTCTACTAAAAATACAAAAAATTAGCCGGGCATGATGGCAGGTGCCTGTAAT
CCCAGCTACTTGGGAGGCTGAAGCGGAAGAATCGCTTGAACCCAGAGGTGGAGGTTGCAGTGAGCCG
AGATCGTGCCATTGCACTGTAACCTGGGTGACTGAGCAAACTCTGTCTCAAAATAATAATAACAATA
TAATAATAATAATAGCCATCCTTTATTGTACCCTTACTGGGTAAATCGTATTATACCACATTACCTCAT
TTTAATTTTTTACTGACCTGCACTTTATACAAAGCAACAAGCCTCCAGGACATTAAAATTCATGCAAAG
TTATGCTCATGTTATATTATTTTCTTACTTAAAGAAGGATTTATTAGTGGCTGGGCATGGTGGCGTGCA
CCTGTAATCCCAGGTACTCAGGAGGCTGAGACGGGAGAATTGCTTGACCCCAGGCGGAGGAGGTTAC
AGTGAGTCGAGATCGTACCTGAGCGACAGAGCGAGACTCCGTCTCAAAAAAAAAAAAAAGGAGGGT
TTATTAATGAGAAAGTTTGTTAATATGTAGCAAAGGCTTTTCCAATGGGTGAATAAAAAACACATTCC
ATTAAGTCAAGCTGGGAGCAGTGGCATATACCTATAGTCCCAGCTGCACAGGAGGCTGAGACAGGAG
GATTGCTTGAAGCCAGGAATTGGAGATCAGCCTGGGCAACACAGCAAGATCCTATCTCTTAAAAAAA
GAAAAAAAAACCTATTAATAATAAAACAGTATAAACAAAAGCTAAATAGGTAAAATATTTTTTCTGA
AATAAAATATTTTTTGTAGTCTGATGGAAATGTTTAAAGTGCAGTAGGCCAGTGCCAGTGAGAAAATAA
ATAACATCATACATGTTTGTATGTGTTGCATCTTGCTTCTACTGAAAGTTTCAGTGCACCCCACTTAC
TTAGAACTCGGTGACATGATGTACTCCTTTATCTGGGACACAGCACAAAAGAGGTATGCAGTGGGGCT
GCTCTGACATGAAAGTGGAAGTTAAGGAATCTGGGCTCTTATGGGGTCCCTGTGGGCCAGCCCTTCAG
GCCTATTTTACTTTTCATTTTACATATAGCTCTAATTGGTTTGATTATCTCGTTCCCAAGGCAGTGGGAG
ATCCCCATTTAAGGAAAGAAAAGGGGCCTGGCACAGTGGCTCATGCCTGTAATCCCAGCACTTTGGG
AGGCTGAGGCAAGTGTATCACCTGAGGTCAGGAGTTCAAGACCAGCCTGGCCAACATGGCAAAATCC
CGTCTCTACTAAAAATATTAATAAAATTGGCTGGGCGTGGTGGTTCGTGCCTATAATTTTCACTACTCA
GGAGGCTGAGGCAGGAGAATCGCTGTAACCTGGGGGGTGGAGGTTGCAGTGAGACGAGATCATGCCA
CTTCACTCCAGCCTGGCCAACAGAGCCATACTCCGTCTCAAATAAATAAATAAATAAATAAAGGGACT
TCAAACACATGAACAGCAGCCAGGGGAAGAATCAAAATCATATTCTGTCAAGCAAACCTGGAAAAGTA
CCACTGTGTGTACCAATAGCCTCCCCACCACAGACCCTGGGAGCATCGCCTCATTTATGGTGTGGTCC
AGTCATCCATGTGAAGGATGAGTTTCCAGGAAAAGGTTATTAAATATTTCACTGTAACATACTGGAGGA
GGTGAGGAATTGCATAATACAATCTTAGAAAACCTTTTTTTTCCCCTTTCTATTTTTTGTAGACAGGATCT
CACTTTGGCACTCAGGCTGGAGGACAGTGGTACAATCAAAGCTCATGGCAGCCTCGACCTCCCTGGGC
TTGGGCAATCCTCCACAGGTGTGCACCTCCATAGCTGGCTAATTTGTGTATTTTTTGTAGAGATGGGG
TTTACCATGTTGCCAGGCTGGTCTCTAACACTTAGGCTCAAGTGATCCACCTGCCTCGTCTCTCCCAA
GATGCTGGGATTACAGGTGTGTGCCACAGGTGTTTCATCAGAAAGCTTTTTTCTATTATTTTTTACCTTCTT
GAGTGGGTAGAACCTCAGCCACATAGAAAATAAAATGTTCTGGCATGACTTATTTAGCTCTCTGGAAT
TACAAAGAAGGAATGAGGTGTGTAAGAGAACTGGGTTTTTGAATCACAAATTTAGAATTTAATC
GAAACTCTGCCTCTTACTTGTGTTGTAGACACTGACAGTGGCCTCATGTTTTTTTTTTTTTAAATCTATAA
AATGGAGATATCTAACATGTTGAGCCTGGGCCCACAGGCAAAGCACAAATCCTGATGTGAGAAGTACT
CAGTTCATGACAACTGTTGTTCTCACATGCATAGCATAATTTTCATATTCACATTGGAGGACTTCTCCCA
AAATATGGATGACGTTCCCTACTCAACCTTGAACCTAATCAAAATACTCAGTTTACTTAACTTCGTATT
AGATTCTGATTCCCTGGAACCATTTATCGTGTGCCTTACCATGCTTATATTTTACTTGATCTTTTGCATA

CCTTCTAAAAC TATTTTAGCCAATTTAAAATTTGACAGTTTGCATTAAATTATAGGTTTACAATATGCT
TTATCCAGCTATACCTGCCCCAAATTCTGACAGATGCTTTTGCCACCTCTAAAGGAAGACCCATGTTCA
TAGTGATGGAGTTTGTGTGGACTAACCATGCAAGGTTGCCAAGGAAAAATCGCTTTACGCTTCCAAGG
TACACACTAAGATGAAAGTAATTTTAGTCCGTGTCCAGTTGGATTCTTGGCACATAGTTATCTTCTGCT
AGAACAACTAAAACAGCTACATGCCAGCAAGGGAGAAAGGGGAAGGAGGGGCAAAGTTTGAAT
TTCATGTAAATTTATGCTGTTCAAAACGACGAGTTCATGACTTTGTGTATAGAGTAAGAAATGCCTTTT
CTTTTTTGAGACAGAGTCTTGCTCTGTACCCAGGCTGGAGTGCAGTGGCACGATCTGGGCTCACTAC
AACCTCCGCTCCTGGGTTCAAGCAATTCTCTGCCTCAGCCTCCCGAGTAGCTGGGATTACAGGTGCC
TGCCACCACACCCGGCTAATTTTTGTATTTTAGTAGAGACGGGGTTTCACCATCATGGCCAGGCTGGT
CTTGAACCTCTGACCTAGTAATCCACCTGCCTCCGCTCCCAAAGTGCTGGGATTACAGGCGTGAGCC
ACTGCACCCAGCCAGAAATGCCTTCTAATCTTTGGTTTATCTTAATTAGCCAGGACACTTGGAGTGCAT
CCCGAAGTACCTGATCAGTGGCCCCCTTTGGAATGTGTAAAACCTCAGCTCACTTATATCCCTGCATCCG
CTACAGAGACAGAATCCAAGCTCATATGTTCCATCTTCTCTGGCTGTATAGTTTAAGGAATGGAAGGC
ACCAGAACAGATTTATTGAAATGTTTATTAGCTGAAGATTTATTTAGACAGTTGAGGAAAACATCAGC
ACCCAGCAGTAAAATTGGCTCTCAAAGATTTTCTTCTCTGTGGAAAGTCAGACCTCTGAGGCCCCAT
CCAGGTAGAAGTACTAGTGCAAGAAGGGCCTCTGCTGTCCACTTGTGTTTCTGTGATCTGTGGGAACA
TTGTTAACGCCACATCTTGACCTCAAATTTGTTTAGCTCCTGGCCAGACACGGTGGCTCACACCTGTAAT
CCCAGCACTTTGAGAGGCTGAGGCAGGTGGATCACCTGAGGTTAGGAGTTCGAGGCCAGCCTGGTCA
ACATGGTAAAACCCCGCCTCTACTAAAAATACAAAAATTAGCTGGCCGTAGTGGCGCACGCCTGTTAT
CCCAGCTACTCGGGAGGCTGAGGCAGGAGAATTGCTTGAACCTGGGTGGTGGAGGTTGCAGTGAGCC
GAGATTACACCACTGCACTCCAGCCTGGGTGACAAGAGGGAAACTCCATTAAAAAAATGTAATTCCT
GTGTCTGCCATCTTAAGTGTAAGGTGGCTAAATTATATAGAAAAATAAGACAATATCATTTCCTCAAT
TACATTCTTTCTACCGCACTCTATGATGCTAGCTGAGATTTTCCAAAAGAAAATGGCTTAAATAAA
ACCCTAAGAGAAAGAAAACTTTAAATCCCTCCAAAGCTCAAAAGTAATAGAAACAGATGAGTTTGG
AGTCAGGATTTCTCTGTAAGATTGCCTAGGCTGTGTACTGCACATCTCCAGGTGCCACTGTTGACAGA
GATTATACTACAATGTGAAGTGAATGGTGCCACTGACAGTTATGCAAACCGTCCAGAGCATAGCCA
CCTGATCCTGCTGGGATTCCTCTTGCCAGTCCATCAGCAGTTCCTTTGAAAGTTTCACCAAACATCCC
TTAAATCTGCCCTCTCCTGCCCCGTCCCCAGTGGAGGTCTCATCATTTTTCACCTGCATTTTTCAGGA
GCTTTCTTATATCCACCTTCCTCCTTTTCTCTCAGCCCATCATCTAGCTACACAGTCTCCAGGGTAAGCT
TTCAGAAAGGCAATCTCTTGTCTGTAAAACCTAAGCAGGACCAAGGCCAAGTTTCTTAGCCTGAAAAA
TGTGCTTTTCTGACTGAACTGTTTCAGGCACTGACTCTACATATAATTATGCTTTTCTACCCCTCACACT
CAACACTTTGACTCCAGCAATCCCAAATCCCCAGATCCCTAAGTGTGCTGTGCTATTTTCACGTGGCTC
TCAGACTTGGCCAGTGCTGTTTCCATTTTGGTCTTTATTTCCACATCTCTGCCTGGGGGGTAGATTCT
ACCCTGAAAAATGTTCTTGGCACAGCCTTGCAAACCTCCTCCTCCACTCAGCCTCTGCCTGGATGCCCTT
GATTGTTCCATGTCTTCAGCATAACCATGTTTGTCTTTCCAGCACTGACCTACCATGTGTACCCCTGC
TTGGCTGTACCTTCATGAGGCTAGGACTATGTGTCTCTTTGTTGACTGCTGTTGCCCTAGCATCTTG
CACAGTTCCTTGACACAATTAGAGCTCTATAAATGTCAAATAAATGTGTTATAATTATATGTTTAAG
ATAGTTGTTCAAATAAACTCTAAATAACCCCAA (SEQ ID NO: 160)

[000200] An example mouse FXN gene nucleotide sequence, corresponding to Gene ID
2395; NM_008044.3 is as follows:

GGAGCGGCCGCGGAGCTGGAGTAGCATGTGGGCGTTCGGAGGTCGCGCAGCCGTGGGCTTGCTGCC
CGGACGGCGTCCCGGGCCTCCGCCTGGGTCGGGAACCCGCGCTGGAGGGAACCGATCGTAACCTGCG
GCCGCCGAGGCCTACATGTACAGTCAACGCCGGCGCCACCCGCCACGCCATTTGAACCTCCACTAC
CTCCAGATTCTGAACATCAAAAAGCAGAGCGTCTGCGTGGTGCAATTTGAGGAACTTGGGGACATTGG
ACAACCCAAGCTCTCTAGACGAGACAGCGTATGAAAGACTGGCGGAAGAGACCCTGGACTCCCTGGC
CGAGTTCTTTGAAGACCTCGCAGACAAGCCCTATACCCTGGAGGACTACGATGTCTCTTTTGGGGATG
GCGTGCTCACCATTAAGCTGGGCGGGGATCTAGGGACCTACGTGATCAACAAGCAGACCCCCAAACAA
GCAAATCTGGCTGTCTTCTCCTTCCAGCGGCCCAAGCGCTATGACTGGACCGGGAAGAACTGGGTGT
ACTCTCATGACGGCGTGTCTCTGCATGAGCTGCTGGCCAGGGAGCTGACTAAAGCTTTAAACACCAAA
CTGGACTTGTCTTCATTGGCCTATTCTGGAAAAGGCACCTTGACTGCCAGCCAGATTCCAAGACATTAA
ACACTGTCAGGTGAAGACCCCCAGCCTCCTCCTGTAGCTGAATGTCTGCCTTCCCATACTGCTCCTGA
AGATAGTCACACCGTGTGTGACAGCTCTGTGAAAAAAGTGTGTTCCCTCCCACCCTGTCCCCGGACCT
GGCTCTTCATTTCTACAGACATTTGTTAGGATTATGTCATTTGCTCCCCAACCTGAGACCTCTGGTCTC
TTAGAAAGTCTTATATGCTGGGCAGTGGTGGCGCACGCCTTTAATCCCAGCACTCGGGAGGCAGAGGC
AGGCGGATTTCTGAGTTCGAGGCCAGCCTGGTCTACAGAGTGAGTTCCAGGACAGCCAGGACTACAC
AGAGAAACCCTGTCTCGAAAAAAAAAAAAAAAAAAGAAAGAAAGAAAGTCTTACACCACAAGTGTG
TCCATGATATAACAGCCTCAAAATGTCTTACACTGTGTGTGCTAATAACCTACACCATGTGTGCTAAT
AACCTCCTGAAAAGGAAAAAGGCTCAGAGGGAGACATGAGTCGTTCCCACTCTTCCATTGTCTCTGAA
AAGATACTCTAAAAGTAACTTCTAAATGTACCCAAGACTCCAAGTATGTACACTTCTGAGTCCTGAGC
AGCAAAGAGTCAAAAGAAACCATCTTAAAATGCCCTTTCGTGCTTTGTACCTACACTCGGTACCCAG
GACCTGGTGCTATTAACCTCTGTGCCTTCATAGTGGGGGTCATTTACACAGTTGGCAGCTACGACATGG
ACCTGAGATGTCTGAAAATTTTGAAAATTGAGCTGGGCATGGTGGGGCATGCCTTTAATCCCAGCAAT
CAGGTGGCAGAGGCATGCAGATATCTCGGTGAGTTGAGGCCAGCCTGGTCTATAAATCCAGGAGAG
TCAGGCCAATTACACAGAGAAACCCTGTCTAAGGAAAATACGAAGAAAATTTGAGCTGGAGAGATCA
CTTAGTCCACACAAGCATGAAGACTCAAGTTTGATCCTAGGCGTCCACGTTTAAAGCCCAGGCATATT
CTTCACTCGGAAAGTGGAGATGAGGGGCTTGACGCTCAGCAGTAAGCCTGGGGTCTCTGAGAAACA
CTATTTCAAAGAAGGAAACTTGCCTGGCTTCAGTTGACCTGTCCTACACATATGTGCACATGCACTAG
TATAGACATAAACATGCACACAAATTCACACATGTTAAATAAATGCAGAAATAACTACAGGCAAGGA
GGACAGACAAAAATCCCTACCATAAACCAAAGAACTAAACAGTGTGATGGAGCCGAGGTCTCGGTTA
TCCATGAGAGAGATGTCTGTACTGGTACAGAGAGCCCGGCCCTTCAATTTCCAATCTACTCAGGGAGAG
GGTAGAATATAGCTGATACCTGACATCCAGTGGAGTGGACCTATCAGGCCATCCACAAAGCTCTCCTT
GTTCCCACTGGGTAGGTGGAAGAAATGGTATTGTTCTTGCTACTGCTCTGTTAGAATTTTCAATGAATT
CCTAGGGAGCTAGCAGCTGCCCCTTGCTCTCTCTGCTGAATCCGGAGCACCATTGCCCTGCCTTAAGT
GTGACAGGCTGCGCTTTGTACTGGAAGCAACACAGCTCCAGAACACCCACACGGAGCAACTCTAAAC
TCGGGTTTGTTCGGGTTCACTTCGTTTCTAACTGAAGGAAAATTGAGAGCAGGGACTCTAGCCCAGT
GTGAAGGCTTGCCTAGCATGCAGAAGGGCCCTAAAGTTCCATCCCCACACTACAAAGGGCTGAGAGA
TTTGTCAAGTGAACACTCTTATGCAAATGCCAGCAGAGGCTATGCAGGGTGAAGTGAACACATTACAT
CATAGACAAAACAATGGAACAGTGTAAACAGGCTAAGTGACTATTTAAGATATTTCTTCTTCACAAT
TTTTTTTTTAGTCTGGTGGAATTTTTGAGTGGTGTAAGTCGGTGCTAGAGAGATAATAAATAGGACC
ATGTGTGGACATGCCTATGGGTGTCCCTTTGTCTTCTTATGAAAGACACACACACACCCACACCCCG
CTTGACCCTTATCAGACCTTCAGAATGTGCACAGGGCGCGTTCTGAATGTGTATGGACGTTAGGGAGT
CAGATGTTATGGGCTCCTCCTGGACCAGTTTTTGGACTTCTTAACTTTCACCTTTATGTATTTCTCTGACT

GGGTTTCAAGGCAGCCTCGATCACACTTAAGAGAGAGTATGAACACTGTGTTGTGTGAGTCAAGTCAT
TCTGAACTCCAGGCATGGGGATGCTCTTCTGTAGTCCTGGCACTTTGAACTCCAAGGCTCAAAGGTAA
AAGAAGGATGGAAGTTTGGACTTGA (SEQ ID NO: 161)

a. Oligonucleotide Size/Sequence

[000201] Oligonucleotides may be of a variety of different lengths, e.g., depending on the format. In some embodiments, an oligonucleotide is 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 35, 40, 45, 50, 75, or more nucleotides in length. In some embodiments, the oligonucleotide is 8 to 50 nucleotides in length, 8 to 40 nucleotides in length, 8 to 30 nucleotides in length, 10 to 15 nucleotides in length, 10 to 20 nucleotides in length, 15 to 25 nucleotides in length, 21 to 23 nucleotides in lengths, 20 to 25 nucleotides in length, etc.

[000202] In some embodiments, a nucleic acid sequence of an oligonucleotide for purposes of the present disclosure is “complementary” to a target nucleic acid when it is specifically hybridizable to the target nucleic acid. In some embodiments, an oligonucleotide hybridizing to a target nucleic acid (e.g., an mRNA or pre-mRNA molecule) results in modulation of activity or expression of the target (e.g., decreased mRNA translation, altered pre-mRNA splicing, exon skipping, target mRNA degradation, etc.). In some embodiments, a nucleic acid sequence of an oligonucleotide has a sufficient degree of complementarity to its target nucleic acid such that it does not hybridize non-target sequences under conditions in which avoidance of non-specific binding is desired, e.g., under physiological conditions. Thus, in some embodiments, an oligonucleotide may be at least 80%, at least 85%, at least 90%, at least 91%, at least 92%, at least 93%, at least 94%, at least 95%, at least 96%, at least 97%, at least 98%, at least 99% or 100% complementary to the consecutive nucleotides of a target nucleic acid. In some embodiments a complementary nucleotide sequence need not be 100% complementary to that of its target to be specifically hybridizable or specific for a target nucleic acid. In certain embodiments, oligonucleotides comprise one or more mismatched nucleobases relative to the target nucleic acid. In certain embodiments, activity relating to the target is reduced by such mismatch, but activity relating to a non-target is reduced by a greater amount (i.e., selectivity for the target nucleic acid is increased and off-target effects are decreased).

[000203] In some embodiments, the FXN-targeting oligonucleotide comprises a nucleotide sequence comprising a region complementary to a target region that comprises at least 10 continuous nucleotides (e.g., at least 10, at least 12, at least 14, at least 16, at least 18, at least 20 or more continuous nucleotides) in SEQ ID NO: 160 or SEQ ID NO: 161. In some embodiments, the FXN-targeting oligonucleotide comprises a nucleotide sequence comprising a

region complementary to a target region that comprises GAA trinucleotide repeats. In some embodiments, the FXN-targeting oligonucleotide comprises a nucleotide sequence comprising a region complementary to expanded GAA trinucleotide repeats. In some embodiments, the region of complementarity is complementary with at least 8 consecutive nucleotides of a target nucleic acid. In some embodiments, an oligonucleotide may contain 1, 2 or 3 base mismatches compared to the portion of the consecutive nucleotides of target nucleic acid. In some embodiments the oligonucleotide may have up to 3 mismatches over 15 bases, or up to 2 mismatches over 10 bases.

[000204] In some embodiments, an oligonucleotide comprises at least 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, or 20 consecutive nucleotides of a sequence comprising any one of SEQ ID NOs: 165-176. In some embodiments, an oligonucleotide comprises a sequence comprising any one of SEQ ID NOs: 165-176. In some embodiments, an oligonucleotide comprises a sequence that shares at least 70%, 75%, 80%, 85%, 90%, 95%, or 97% sequence identity with at least 12 or at least 15 consecutive nucleotides of any one of SEQ ID NOs: 165-176.

[000205] In some embodiments, an oligonucleotide comprises a region of complementarity to nucleotide sequence set forth in any one of SEQ ID NO: 162-164. In some embodiments, an oligonucleotide comprises at least 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, or 20 nucleotides (*e.g.*, consecutive nucleotides) that are complementary to a nucleotide sequence set forth in any one of SEQ ID NOs: 162-164. In some embodiments, an oligonucleotide comprises a sequence that is at least 70%, 75%, 80%, 85%, 90%, 95%, 97%, 99%, or 100% complementary with at least 12 or at least 15 consecutive nucleotides of any one of SEQ ID NO: 162-164.

[000206] In some embodiments, the oligonucleotide is complementary (*e.g.*, at least 85% at least 90%, at least 95%, or 100%) to a target sequence of any one of the oligonucleotides provided herein (*e.g.*, the oligonucleotides listed in **Table 8**). In some embodiments, such target sequence is 100% complementary to the oligonucleotide listed in **Table 8**.

[000207] In some embodiments, it should be appreciated that methylation of the nucleobase uracil at the C5 position forms thymine. Thus, in some embodiments, a nucleotide or nucleoside having a C5 methylated uracil (or 5-methyl-uracil) may be equivalently identified as a thymine nucleotide or nucleoside.

[000208] In some embodiments, any one or more of the thymine bases (T's) in any one of the oligonucleotides provided herein (*e.g.*, the oligonucleotides listed in **Table 8**) may optionally be uracil bases (U's), and/or any one or more of the U's may optionally be T's.

b. Oligonucleotide Modifications

[000209] The oligonucleotides described herein may be modified, e.g., comprise a modified sugar moiety, a modified internucleoside linkage, a modified nucleotide or nucleoside and/or (e.g., and) combinations thereof. In addition, in some embodiments, oligonucleotides may exhibit one or more of the following properties: do not mediate alternative splicing; are not immune stimulatory; are nuclease resistant; have improved cell uptake compared to unmodified oligonucleotides; are not toxic to cells or mammals; have improved endosomal exit internally in a cell; minimizes TLR stimulation; or avoid pattern recognition receptors. Any of the modified chemistries or formats of oligonucleotides described herein can be combined with each other. For example, one, two, three, four, five, or more different types of modifications can be included within the same oligonucleotide.

[000210] In some embodiments, certain nucleotide or nucleoside modifications may be used that make an oligonucleotide into which they are incorporated more resistant to nuclease digestion than the native oligodeoxynucleotide or oligoribonucleotide molecules; these modified oligonucleotides survive intact for a longer time than unmodified oligonucleotides. Specific examples of modified oligonucleotides include those comprising modified backbones, for example, modified internucleoside linkages such as phosphorothioates, phosphotriesters, methyl phosphonates, short chain alkyl or cycloalkyl intersugar linkages or short chain heteroatomic or heterocyclic intersugar linkages. Accordingly, oligonucleotides of the disclosure can be stabilized against nucleolytic degradation such as by the incorporation of a modification, e.g., a nucleotide or nucleoside modification.

[000211] In some embodiments, an oligonucleotide may be of up to 50 or up to 100 nucleotides in length in which 2 to 10, 2 to 15, 2 to 16, 2 to 17, 2 to 18, 2 to 19, 2 to 20, 2 to 25, 2 to 30, 2 to 40, 2 to 45, or more nucleotides or nucleoside of the oligonucleotide are modified nucleotides/nucleosides. The oligonucleotide may be of 8 to 30 nucleotides in length in which 2 to 10, 2 to 15, 2 to 16, 2 to 17, 2 to 18, 2 to 19, 2 to 20, 2 to 25, 2 to 30 nucleotides or nucleoside of the oligonucleotide are modified nucleotides/nucleosides. The oligonucleotide may be of 8 to 15 nucleotides in length in which 2 to 4, 2 to 5, 2 to 6, 2 to 7, 2 to 8, 2 to 9, 2 to 10, 2 to 11, 2 to 12, 2 to 13, 2 to 14 nucleotides or nucleoside of the oligonucleotide are modified nucleotides/nucleosides. Optionally, the oligonucleotides may have every nucleotide or nucleoside except 1, 2, 3, 4, 5, 6, 7, 8, 9, or 10 nucleotides/nucleosides modified. Oligonucleotide modifications are described further herein.

c. Modified Nucleosides

[000212] In some embodiments, the oligonucleotide described herein comprises at least one nucleoside modified at the 2' position of the sugar. In some embodiments, an oligonucleotide comprises at least one 2'-modified nucleoside. In some embodiments, all of the nucleosides in the oligonucleotide are 2'-modified nucleosides.

[000213] In some embodiments, the oligonucleotide described herein comprises one or more non-bicyclic 2'-modified nucleosides, e.g., 2'-deoxy, 2'-fluoro (2'-F), 2'-O-methyl (2'-O-Me), 2'-O-methoxyethyl (2'-MOE), 2'-O-aminopropyl (2'-O-AP), 2'-O-dimethylaminoethyl (2'-O-DMAOE), 2'-O-dimethylaminopropyl (2'-O-DMAP), 2'-O-dimethylaminoethoxyethyl (2'-O-DMAEOE), or 2'-O-N-methylacetamido (2'-O-NMA) modified nucleoside.

[000214] In some embodiments, the oligonucleotide described herein comprises one or more 2'-4' bicyclic nucleosides in which the ribose ring comprises a bridge moiety connecting two atoms in the ring, e.g., connecting the 2'-O atom to the 4'-C atom via a methylene (LNA) bridge, an ethylene (ENA) bridge, or a (S)-constrained ethyl (cEt) bridge. Examples of LNAs are described in International Patent Application Publication WO/2008/043753, published on April 17, 2008, and entitled "*RNA Antagonist Compounds For The Modulation Of PCSK9*", the contents of which are incorporated herein by reference in its entirety. Examples of ENAs are provided in International Patent Publication No. WO 2005/042777, published on May 12, 2005, and entitled "*APP/ENA Antisense*"; Morita et al., *Nucleic Acid Res., Suppl* 1:241-242, 2001; Surono et al., *Hum. Gene Ther.*, 15:749-757, 2004; Koizumi, *Curr. Opin. Mol. Ther.*, 8:144-149, 2006 and Horie et al., *Nucleic Acids Symp. Ser (Oxf)*, 49:171-172, 2005; the disclosures of which are incorporated herein by reference in their entireties. Examples of cEt are provided in US Patents 7,101,993; 7,399,845 and 7,569,686, each of which is herein incorporated by reference in its entirety.

[000215] In some embodiments, the oligonucleotide comprises a modified nucleoside disclosed in one of the following United States Patent or Patent Application Publications: US Patent 7,399,845, issued on July 15, 2008, and entitled "*6-Modified Bicyclic Nucleic Acid Analogs*"; US Patent 7,741,457, issued on June 22, 2010, and entitled "*6-Modified Bicyclic Nucleic Acid Analogs*"; US Patent 8,022,193, issued on September 20, 2011, and entitled "*6-Modified Bicyclic Nucleic Acid Analogs*"; US Patent 7,569,686, issued on August 4, 2009, and entitled "*Compounds And Methods For Synthesis Of Bicyclic Nucleic Acid Analogs*"; US Patent 7,335,765, issued on February 26, 2008, and entitled "*Novel Nucleoside And Oligonucleotide Analogues*"; US Patent 7,314,923, issued on January 1, 2008, and entitled "*Novel Nucleoside And Oligonucleotide Analogues*"; US Patent 7,816,333, issued on October 19, 2010, and entitled "*Oligonucleotide Analogues And Methods Utilizing The Same*" and US Publication Number

2011/0009471 now US Patent 8,957,201, issued on February 17, 2015, and entitled “*Oligonucleotide Analogues And Methods Utilizing The Same*”, the entire contents of each of which are incorporated herein by reference for all purposes.

[000216] In some embodiments, the oligonucleotide comprises at least one modified nucleoside that results in an increase in T_m of the oligonucleotide in a range of 1 °C, 2 °C, 3 °C, 4 °C, or 5 °C compared with an oligonucleotide that does not have the at least one modified nucleoside. The oligonucleotide may have a plurality of modified nucleosides that result in a total increase in T_m of the oligonucleotide in a range of 2 °C, 3 °C, 4 °C, 5 °C, 6 °C, 7 °C, 8 °C, 9 °C, 10 °C, 15 °C, 20 °C, 25 °C, 30 °C, 35 °C, 40 °C, 45 °C or more compared with an oligonucleotide that does not have the modified nucleoside.

[000217] The oligonucleotide may comprise a mix of nucleosides of different kinds. For example, an oligonucleotide may comprise a mix of 2'-deoxyribonucleosides or ribonucleosides and 2'-fluoro modified nucleosides. An oligonucleotide may comprise a mix of deoxyribonucleosides or ribonucleosides and 2'-O-Me modified nucleosides. An oligonucleotide may comprise a mix of 2'-fluoro modified nucleosides and 2'-O-methyl modified nucleosides. An oligonucleotide may comprise a mix of bridged nucleosides and 2'-fluoro or 2'-O-methyl modified nucleotides. An oligonucleotide may comprise a mix of non-bicyclic 2'-modified nucleosides (e.g., 2'-O-MOE) and 2'-4' bicyclic nucleosides (e.g., LNA, ENA, cEt). An oligonucleotide may comprise a mix of 2'-fluoro modified nucleosides and 2'-O-Me modified nucleosides. An oligonucleotide may comprise a mix of 2'-4' bicyclic nucleosides and 2'-MOE, 2'-fluoro, or 2'-O-Me modified nucleosides. An oligonucleotide may comprise a mix of non-bicyclic 2'-modified nucleosides (e.g., 2'-MOE, 2'-fluoro, or 2'-O-Me) and 2'-4' bicyclic nucleosides (e.g., LNA, ENA, cEt).

[000218] The oligonucleotide may comprise alternating nucleosides of different kinds. For example, an oligonucleotide may comprise alternating 2'-deoxyribonucleosides or ribonucleosides and 2'-fluoro modified nucleosides. An oligonucleotide may comprise alternating deoxyribonucleosides or ribonucleosides and 2'-O-Me modified nucleosides. An oligonucleotide may comprise alternating 2'-fluoro modified nucleosides and 2'-O-Me modified nucleosides. An oligonucleotide may comprise alternating bridged nucleosides and 2'-fluoro or 2'-O-methyl modified nucleotides. An oligonucleotide may comprise alternating non-bicyclic 2'-modified nucleosides (e.g., 2'-O-MOE) and 2'-4' bicyclic nucleosides (e.g., LNA, ENA, cEt). An oligonucleotide may comprise alternating 2'-4' bicyclic nucleosides and 2'-MOE, 2'-fluoro, or 2'-O-Me modified nucleosides. An oligonucleotide may comprise alternating non-bicyclic 2'-modified nucleosides (e.g., 2'-MOE, 2'-fluoro, or 2'-O-Me) and 2'-4' bicyclic nucleosides (e.g., LNA, ENA, cEt).

[000219] In some embodiments, an oligonucleotide described herein comprises a 5'-vinylphosphonate modification, one or more abasic residues, and/or one or more inverted abasic residues.

d. Internucleoside Linkages / Backbones

[000220] In some embodiments, oligonucleotide may contain a phosphorothioate or other modified internucleoside linkage. In some embodiments, the oligonucleotide comprises phosphorothioate internucleoside linkages. In some embodiments, the oligonucleotide comprises phosphorothioate internucleoside linkages between at least two nucleosides. In some embodiments, the oligonucleotide comprises phosphorothioate internucleoside linkages between all nucleosides. For example, in some embodiments, oligonucleotides comprise modified internucleoside linkages at the first, second, and/or (e.g., and) third internucleoside linkage at the 5' or 3' end of the nucleotide sequence.

[000221] Phosphorus-containing linkages that may be used include, but are not limited to, phosphorothioates, chiral phosphorothioates, phosphorodithioates, phosphotriesters, aminoalkylphosphotriesters, methyl and other alkyl phosphonates comprising 3'-alkylene phosphonates and chiral phosphonates, phosphinates, phosphoramidates comprising 3'-amino phosphoramidate and aminoalkylphosphoramidates, thionophosphoramidates, thionoalkylphosphonates, thionoalkylphosphotriesters, and boranophosphates having normal 3'-5' linkages, 2'-5' linked analogs of these, and those having inverted polarity wherein the adjacent pairs of nucleoside units are linked 3'-5' to 5'-3' or 2'-5' to 5'-2'; see US patent nos. 3,687,808; 4,469,863; 4,476,301; 5,023,243; 5,177,196; 5,188,897; 5,264,423; 5,276,019; 5,278,302; 5,286,717; 5,321,131; 5,399,676; 5,405,939; 5,453,496; 5,455,233; 5,466,677; 5,476,925; 5,519,126; 5,536,821; 5,541,306; 5,550,111; 5,563,253; 5,571,799; 5,587,361; and 5,625,050.

[000222] In some embodiments, oligonucleotides may have heteroatom backbones, such as methylene(methylimino) or MMI backbones; amide backbones (see De Mesmaeker et al. *Ace. Chem. Res.* 1995, 28:366-374); morpholino backbones (see Summerton and Weller, U.S. Pat. No. 5,034,506); or peptide nucleic acid (PNA) backbones (wherein the phosphodiester backbone of the oligonucleotide is replaced with a polyamide backbone, the nucleotides being bound directly or indirectly to the aza nitrogen atoms of the polyamide backbone, see Nielsen et al., *Science* 1991, 254, 1497).

e. Stereospecific Oligonucleotides

[000223] In some embodiments, internucleotidic phosphorus atoms of oligonucleotides are chiral, and the properties of the oligonucleotides are adjusted based on the configuration of the

chiral phosphorus atoms. In some embodiments, appropriate methods may be used to synthesize P-chiral oligonucleotide analogs in a stereocontrolled manner (e.g., as described in Oka N, Wada T, Stereocontrolled synthesis of oligonucleotide analogs containing chiral internucleotidic phosphorus atoms. Chem Soc Rev. 2011 Dec;40(12):5829-43.) In some embodiments, phosphorothioate containing oligonucleotides comprise nucleoside units that are joined together by either substantially all Sp or substantially all Rp phosphorothioate intersugar linkages are provided. In some embodiments, such phosphorothioate oligonucleotides having substantially chirally pure intersugar linkages are prepared by enzymatic or chemical synthesis, as described, for example, in US Patent 5,587,261, issued on December 12, 1996, the contents of which are incorporated herein by reference in their entirety. In some embodiments, chirally controlled oligonucleotides provide selective cleavage patterns of a target nucleic acid. For example, in some embodiments, a chirally controlled oligonucleotide provides single site cleavage within a complementary sequence of a nucleic acid, as described, for example, in US Patent Application Publication 20170037399 A1, published on February 2, 2017, entitled "CHIRAL DESIGN", the contents of which are incorporated herein by reference in their entirety.

f. Gapmers

[000224] In some embodiments, the oligonucleotide described herein is a gapmer. A gapmer oligonucleotide generally has the formula 5'-X-Y-Z-3', with X and Z as flanking regions around a gap region Y. In some embodiments, flanking region X of formula 5'-X-Y-Z-3' is also referred to as X region, flanking sequence X, 5' wing region X, or 5' wing segment. In some embodiments, flanking region Z of formula 5'-X-Y-Z-3' is also referred to as Z region, flanking sequence Z, 3' wing region Z, or 3' wing segment. In some embodiments, gap region Y of formula 5'-X-Y-Z-3' is also referred to as Y region, Y segment, or gap-segment Y. In some embodiments, each nucleoside in the gap region Y is a 2'-deoxyribonucleoside, and neither the 5' wing region X or the 3' wing region Z contains any 2'-deoxyribonucleosides.

[000225] In some embodiments, the Y region is a contiguous stretch of nucleotides, e.g., a region of 6 or more DNA nucleotides, which are capable of recruiting an RNase, such as RNase H. In some embodiments, the gapmer binds to the target nucleic acid, at which point an RNase is recruited and can then cleave the target nucleic acid. In some embodiments, the Y region is flanked both 5' and 3' by regions X and Z comprising high-affinity modified nucleosides, e.g., one to six high-affinity modified nucleosides. Examples of high affinity modified nucleosides include, but are not limited to, 2'-modified nucleosides (e.g., 2'-MOE, 2'-O-Me, 2'-F) or 2'-4' bicyclic nucleosides (e.g., LNA, cEt, ENA). In some embodiments, the flanking sequences X

and Z may be of 1-20 nucleotides, 1-8 nucleotides, or 1-5 nucleotides in length. The flanking sequences X and Z may be of similar length or of dissimilar lengths. In some embodiments, the gap-segment Y may be a nucleotide sequence of 5-20 nucleotides, 5-15 twelve nucleotides, or 6-10 nucleotides in length.

[000226] In some embodiments, the gap region of the gapmer oligonucleotides may contain modified nucleotides known to be acceptable for efficient RNase H action in addition to DNA nucleotides, such as C4'-substituted nucleotides, acyclic nucleotides, and arabino-configured nucleotides. In some embodiments, the gap region comprises one or more unmodified internucleosides. In some embodiments, one or both flanking regions each independently comprise one or more phosphorothioate internucleoside linkages (e.g., phosphorothioate internucleoside linkages or other linkages) between at least two, at least three, at least four, at least five or more nucleotides. In some embodiments, the gap region and two flanking regions each independently comprise modified internucleoside linkages (e.g., phosphorothioate internucleoside linkages or other linkages) between at least two, at least three, at least four, at least five or more nucleotides.

[000227] A gapmer may be produced using appropriate methods. Representative U.S. patents, U.S. patent publications, and PCT publications that teach the preparation of gapmers include, but are not limited to, U.S. Pat. Nos. 5,013,830; 5,149,797; 5,220,007; 5,256,775; 5,366,878; 5,403,711; 5,491,133; 5,565,350; 5,623,065; 5,652,355; 5,652,356; 5,700,922; 5,898,031; 7,015,315; 7,101,993; 7,399,845; 7,432,250; 7,569,686; 7,683,036; 7,750,131; 8,580,756; 9,045,754; 9,428,534; 9,695,418; 10,017,764; 10,260,069; 9,428,534; 8,580,756; U.S. patent publication Nos. US20050074801, US20090221685; US20090286969, US20100197762, and US20110112170; PCT publication Nos. WO2004069991; WO2005023825; WO2008049085 and WO2009090182; and EP Patent No. EP2,149,605, each of which is herein incorporated by reference in its entirety.

[000228] In some embodiments, the gapmer is 10-40 nucleosides in length. For example, the gapmer may be 10-40, 10-35, 10-30, 10-25, 10-20, 10-15, 15-40, 15-35, 15-30, 15-25, 15-20, 20-40, 20-35, 20-30, 20-25, 25-40, 25-35, 25-30, 30-40, 30-35, or 35-40 nucleosides in length. In some embodiments, the gapmer is 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, or 40 nucleosides in length.

[000229] In some embodiments, the gap region Y in the gapmer is 5-20 nucleosides in length. For example, the gap region Y may be 5-20, 5-15, 5-10, 10-20, 10-15, or 15-20 nucleosides in length. In some embodiments, the gap region Y is 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, or 20 nucleosides in length. In some embodiments, each nucleoside in the gap region Y is a 2'-deoxyribonucleoside. In some embodiments, all nucleosides in the gap

region Y are 2'-deoxyribonucleosides. In some embodiments, one or more of the nucleosides in the gap region Y is a modified nucleoside (e.g., a 2' modified nucleoside such as those described herein). In some embodiments, one or more cytidines in the gap region Y are optionally 5-methyl-cytidines. In some embodiments, each cytidine in the gap region Y is a 5-methyl-cytidines.

[000230] In some embodiments, the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) and the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) are independently 1-20 nucleosides long. For example, the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) and the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) may be independently 1-20, 1-15, 1-10, 1-7, 1-5, 1-3, 1-2, 2-5, 2-7, 3-5, 3-7, 5-20, 5-15, 5-10, 10-20, 10-15, or 15-20 nucleosides long. In some embodiments, the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) and the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) are independently 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, or 20 nucleosides long. In some embodiments, the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) and the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) are of the same length. In some embodiments, the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) and the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) are of different lengths. In some embodiments, the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) is longer than the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula). In some embodiments, the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) is shorter than the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula).

[000231] In some embodiments, the gapmer comprises a 5'-X-Y-Z-3' of 5-10-5, 4-12-4, 3-14-3, 2-16-2, 1-18-1, 3-10-3, 2-10-2, 1-10-1, 2-8-2, 4-6-4, 3-6-3, 2-6-2, 4-7-4, 3-7-3, 2-7-2, 4-8-4, 3-8-3, 2-8-2, 1-8-1, 2-9-2, 1-9-1, 2-10-2, 1-10-1, 1-12-1, 1-16-1, 2-15-1, 1-15-2, 1-14-3, 3-14-1, 2-14-2, 1-13-4, 4-13-1, 2-13-3, 3-13-2, 1-12-5, 5-12-1, 2-12-4, 4-12-2, 3-12-3, 1-11-6, 6-11-1, 2-11-5, 5-11-2, 3-11-4, 4-11-3, 1-17-1, 2-16-1, 1-16-2, 1-15-3, 3-15-1, 2-15-2, 1-14-4, 4-14-1, 2-14-3, 3-14-2, 1-13-5, 5-13-1, 2-13-4, 4-13-2, 3-13-3, 1-12-6, 6-12-1, 2-12-5, 5-12-2, 3-12-4, 4-12-3, 1-11-7, 7-11-1, 2-11-6, 6-11-2, 3-11-5, 5-11-3, 4-11-4, 1-18-1, 1-17-2, 2-17-1, 1-16-3, 1-16-3, 2-16-2, 1-15-4, 4-15-1, 2-15-3, 3-15-2, 1-14-5, 5-14-1, 2-14-4, 4-14-2, 3-14-3, 1-13-6, 6-13-1, 2-13-5, 5-13-2, 3-13-4, 4-13-3, 1-12-7, 7-12-1, 2-12-6, 6-12-2, 3-12-5, 5-12-3, 1-11-8, 8-11-1, 2-11-7, 7-11-2, 3-11-6, 6-11-3, 4-11-5, 5-11-4, 1-18-1, 1-17-2, 2-17-1, 1-16-3, 3-16-1, 2-16-2, 1-15-4, 4-15-1, 2-15-3, 3-15-2, 1-14-5, 2-14-4, 4-14-2, 3-14-3, 1-13-6, 6-13-1, 2-13-5, 5-13-2, 3-13-4, 4-13-3, 1-12-7, 7-12-1, 2-12-6, 6-12-2, 3-12-5, 5-12-3, 1-11-8, 8-11-1, 2-11-7, 7-11-2, 3-11-6, 6-11-3, 4-11-5, 5-11-4, 1-19-1, 1-18-2, 2-18-1, 1-17-3, 3-17-1, 2-17-2, 1-16-4, 4-16-1, 2-16-3, 3-16-2, 1-15-5, 2-15-4, 4-15-2, 3-15-3, 1-14-6, 6-14-1, 2-14-5, 5-14-2, 3-14-4,

4-14-3, 1-13-7, 7-13-1, 2-13-6, 6-13-2, 3-13-5, 5-13-3, 4-13-4, 1-12-8, 8-12-1, 2-12-7, 7-12-2, 3-12-6, 6-12-3, 4-12-5, 5-12-4, 2-11-8, 8-11-2, 3-11-7, 7-11-3, 4-11-6, 6-11-4, 5-11-5, 1-20-1, 1-19-2, 2-19-1, 1-18-3, 3-18-1, 2-18-2, 1-17-4, 4-17-1, 2-17-3, 3-17-2, 1-16-5, 2-16-4, 4-16-2, 3-16-3, 1-15-6, 6-15-1, 2-15-5, 5-15-2, 3-15-4, 4-15-3, 1-14-7, 7-14-1, 2-14-6, 6-14-2, 3-14-5, 5-14-3, 4-14-4, 1-13-8, 8-13-1, 2-13-7, 7-13-2, 3-13-6, 6-13-3, 4-13-5, 5-13-4, 2-12-8, 8-12-2, 3-12-7, 7-12-3, 4-12-6, 6-12-4, 5-12-5, 3-11-8, 8-11-3, 4-11-7, 7-11-4, 5-11-6, 6-11-5, 1-21-1, 1-20-2, 2-20-1, 1-20-3, 3-19-1, 2-19-2, 1-18-4, 4-18-1, 2-18-3, 3-18-2, 1-17-5, 2-17-4, 4-17-2, 3-17-3, 1-16-6, 6-16-1, 2-16-5, 5-16-2, 3-16-4, 4-16-3, 1-15-7, 7-15-1, 2-15-6, 6-15-2, 3-15-5, 5-15-3, 4-15-4, 1-14-8, 8-14-1, 2-14-7, 7-14-2, 3-14-6, 6-14-3, 4-14-5, 5-14-4, 2-13-8, 8-13-2, 3-13-7, 7-13-3, 4-13-6, 6-13-4, 5-13-5, 1-12-10, 10-12-1, 2-12-9, 9-12-2, 3-12-8, 8-12-3, 4-12-7, 7-12-4, 5-12-6, 6-12-5, 4-11-8, 8-11-4, 5-11-7, 7-11-5, 6-11-6, 1-22-1, 1-21-2, 2-21-1, 1-21-3, 3-20-1, 2-20-2, 1-19-4, 4-19-1, 2-19-3, 3-19-2, 1-18-5, 2-18-4, 4-18-2, 3-18-3, 1-17-6, 6-17-1, 2-17-5, 5-17-2, 3-17-4, 4-17-3, 1-16-7, 7-16-1, 2-16-6, 6-16-2, 3-16-5, 5-16-3, 4-16-4, 1-15-8, 8-15-1, 2-15-7, 7-15-2, 3-15-6, 6-15-3, 4-15-5, 5-15-4, 2-14-8, 8-14-2, 3-14-7, 7-14-3, 4-14-6, 6-14-4, 5-14-5, 3-13-8, 8-13-3, 4-13-7, 7-13-4, 5-13-6, 6-13-5, 4-12-8, 8-12-4, 5-12-7, 7-12-5, 6-12-6, 5-11-8, 8-11-5, 6-11-7, or 7-11-6. The numbers indicate the number of nucleosides in X, Y, and Z regions in the 5'-X-Y-Z-3' gapmer.

[000232] In some embodiments, one or more nucleosides in the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) or the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) are modified nucleotides (e.g., high-affinity modified nucleosides). In some embodiments, the modified nucleoside (e.g., high-affinity modified nucleosides) is a 2'-modified nucleoside. In some embodiments, the 2'-modified nucleoside is a 2'-4' bicyclic nucleoside or a non-bicyclic 2'-modified nucleoside. In some embodiments, the high-affinity modified nucleoside is a 2'-4' bicyclic nucleoside (e.g., LNA, cEt, or ENA) or a non-bicyclic 2'-modified nucleoside (e.g., 2'-fluoro (2'-F), 2'-O-methyl (2'-O-Me), 2'-O-methoxyethyl (2'-MOE), 2'-O-aminopropyl (2'-O-AP), 2'-O-dimethylaminoethyl (2'-O-DMAOE), 2'-O-dimethylaminopropyl (2'-O-DMAP), 2'-O-dimethylaminoethoxyethyl (2'-O-DMAEOE), or 2'-O-N-methylacetamido (2'-O-NMA)).

[000233] In some embodiments, one or more nucleosides in the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) are high-affinity modified nucleosides. In some embodiments, each nucleoside in the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) is a high-affinity modified nucleoside. In some embodiments, one or more nucleosides in the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) are high-affinity modified nucleosides. In some embodiments, each nucleoside in the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) is a high-affinity modified nucleoside. In some embodiments, one or

more nucleosides in the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) are high-affinity modified nucleosides and one or more nucleosides in the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) are high-affinity modified nucleosides. In some embodiments, each nucleoside in the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) is a high-affinity modified nucleoside and each nucleoside in the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) is high-affinity modified nucleoside.

[000234] In some embodiments, the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) comprises the same high affinity nucleosides as the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula). For example, the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) and the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) may comprise one or more non-bicyclic 2'-modified nucleosides (e.g., 2'-MOE or 2'-O-Me). In another example, the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) and the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) may comprise one or more 2'-4' bicyclic nucleosides (e.g., LNA or cEt). In some embodiments, each nucleoside in the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) and the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) is a non-bicyclic 2'-modified nucleosides (e.g., 2'-MOE or 2'-O-Me). In some embodiments, each nucleoside in the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) and the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) is a 2'-4' bicyclic nucleosides (e.g., LNA or cEt).

[000235] In some embodiments, the gapmer comprises a 5'-X-Y-Z-3' configuration, wherein X and Z is independently 1-7 (e.g., 1, 2, 3, 4, 5, 6, or 7) nucleosides in length and Y is 6-10 (e.g., 6, 7, 8, 9, or 10) nucleosides in length, wherein each nucleoside in X and Z is a non-bicyclic 2'-modified nucleosides (e.g., 2'-MOE or 2'-O-Me) and each nucleoside in Y is a 2'-deoxyribonucleoside. In some embodiments, the gapmer comprises a 5'-X-Y-Z-3' configuration, wherein X and Z is independently 1-7 (e.g., 1, 2, 3, 4, 5, 6, or 7) nucleosides in length and Y is 6-10 (e.g., 6, 7, 8, 9, or 10) nucleosides in length, wherein each nucleoside in X and Z is a 2'-4' bicyclic nucleosides (e.g., LNA or cEt) and each nucleoside in Y is a 2'-deoxyribonucleoside. In some embodiments, the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) comprises different high affinity nucleosides as the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula). For example, the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) may comprise one or more non-bicyclic 2'-modified nucleosides (e.g., 2'-MOE or 2'-O-Me) and the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) may comprise one or more 2'-4' bicyclic nucleosides (e.g., LNA or cEt). In another example, the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) may comprise one or more non-bicyclic 2'-modified nucleosides

(e.g., 2'-MOE or 2'-O-Me) and the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) may comprise one or more 2'-4' bicyclic nucleosides (e.g., LNA or cEt).

[000236] In some embodiments, the gapmer comprises a 5'-X-Y-Z-3' configuration, wherein X and Z is independently 1-7 (e.g., 1, 2, 3, 4, 5, 6, or 7) nucleosides in length and Y is 6-10 (e.g., 6, 7, 8, 9, or 10) nucleosides in length, wherein each nucleoside in X is a non-bicyclic 2'-modified nucleosides (e.g., 2'-MOE or 2'-O-Me), each nucleoside in Z is a 2'-4' bicyclic nucleosides (e.g., LNA or cEt), and each nucleoside in Y is a 2'-deoxyribonucleoside. In some embodiments, the gapmer comprises a 5'-X-Y-Z-3' configuration, wherein X and Z is independently 1-7 (e.g., 1, 2, 3, 4, 5, 6, or 7) nucleosides in length and Y is 6-10 (e.g., 6, 7, 8, 9, or 10) nucleosides in length, wherein each nucleoside in X is a 2'-4' bicyclic nucleosides (e.g., LNA or cEt), each nucleoside in Z is a non-bicyclic 2'-modified nucleosides (e.g., 2'-MOE or 2'-O-Me) and each nucleoside in Y is a 2'-deoxyribonucleoside.

[000237] In some embodiments, the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) comprises one or more non-bicyclic 2'-modified nucleosides (e.g., 2'-MOE or 2'-O-Me) and one or more 2'-4' bicyclic nucleosides (e.g., LNA or cEt). In some embodiments, the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) comprises one or more non-bicyclic 2'-modified nucleosides (e.g., 2'-MOE or 2'-O-Me) and one or more 2'-4' bicyclic nucleosides (e.g., LNA or cEt). In some embodiments, both the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) and the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) comprise one or more non-bicyclic 2'-modified nucleosides (e.g., 2'-MOE or 2'-O-Me) and one or more 2'-4' bicyclic nucleosides (e.g., LNA or cEt).

[000238] In some embodiments, the gapmer comprises a 5'-X-Y-Z-3' configuration, wherein X and Z is independently 2-7 (e.g., 2, 3, 4, 5, 6, or 7) nucleosides in length and Y is 6-10 (e.g., 6, 7, 8, 9, or 10) nucleosides in length, wherein at least one but not all (e.g., 1, 2, 3, 4, 5, or 6) of positions 1, 2, 3, 4, 5, 6, or 7 in X (the 5' most position is position 1) is a non-bicyclic 2'-modified nucleoside (e.g., 2'-MOE or 2'-O-Me), wherein the rest of the nucleosides in both X and Z are 2'-4' bicyclic nucleosides (e.g., LNA or cEt), and wherein each nucleoside in Y is a 2'-deoxyribonucleoside. In some embodiments, the gapmer comprises a 5'-X-Y-Z-3' configuration, wherein X and Z is independently 2-7 (e.g., 2, 3, 4, 5, 6, or 7) nucleosides in length and Y is 6-10 (e.g., 6, 7, 8, 9, or 10) nucleosides in length, wherein at least one but not all (e.g., 1, 2, 3, 4, 5, or 6) of positions 1, 2, 3, 4, 5, 6, or 7 in Z (the 5' most position is position 1) is a non-bicyclic 2'-modified nucleoside (e.g., 2'-MOE or 2'-O-Me), wherein the rest of the nucleosides in both X and Z are 2'-4' bicyclic nucleosides (e.g., LNA or cEt), and wherein each nucleoside in Y is a 2'-deoxyribonucleoside. In some embodiments, the gapmer comprises a 5'-X-Y-Z-3' configuration, wherein X and Z is independently 2-7 (e.g., 2, 3, 4, 5, 6, or 7)

nucleosides in length and Y is 6-10 (e.g., 6, 7, 8, 9, or 10) nucleosides in length, wherein at least one but not all (e.g., 1, 2, 3, 4, 5, or 6) of positions 1, 2, 3, 4, 5, 6, or 7 in X and at least one of positions but not all (e.g., 1, 2, 3, 4, 5, or 6) 1, 2, 3, 4, 5, 6, or 7 in Z (the 5' most position is position 1) is a non-bicyclic 2'-modified nucleoside (e.g., 2'-MOE or 2'-O-Me), wherein the rest of the nucleosides in both X and Z are 2'-4' bicyclic nucleosides (e.g., LNA or cEt), and wherein each nucleoside in Y is a 2' deoxyribonucleoside.

[000239] Non-limiting examples of gapmers configurations with a mix of non-bicyclic 2'-modified nucleoside (e.g., 2'-MOE or 2'-O-Me) and 2'-4' bicyclic nucleosides (e.g., LNA or cEt) in the 5' wing region of the gapmer (X in the 5'-X-Y-Z-3' formula) and/or the 3' wing region of the gapmer (Z in the 5'-X-Y-Z-3' formula) include: BBB-(D)n-BBBAA; KKK-(D)n-KKKAA; LLL-(D)n-LLLAA; BBB-(D)n-BBBEE; KKK-(D)n-KKKEE; LLL-(D)n-LLLEE; BBB-(D)n-BBBAA; KKK-(D)n-KKKAA; LLL-(D)n-LLLAA; BBB-(D)n-BBBEE; KKK-(D)n-KKKEE; LLL-(D)n-LLLEE; BBB-(D)n-BBBAAA; KKK-(D)n-KKKAAA; LLL-(D)n-LLLAAA; BBB-(D)n-BBBEEE; KKK-(D)n-KKKEEE; LLL-(D)n-LLLEEE; BBB-(D)n-BBBAAA; KKK-(D)n-KKKAAA; LLL-(D)n-LLLAAA; BBB-(D)n-BBBEEE; KKK-(D)n-KKKEEE; LLL-(D)n-LLLEEE; BABA-(D)n-ABAB; KAKA-(D)n-AKAK; LALA-(D)n-ALAL; BEBE-(D)n-EBEB; KEKE-(D)n-EKEK; LELE-(D)n-ELEL; BABA-(D)n-ABAB; KAKA-(D)n-AKAK; LALA-(D)n-ALAL; BEBE-(D)n-EBEB; KEKE-(D)n-EKEK; LELE-(D)n-ELEL; ABAB-(D)n-ABAB; AKAK-(D)n-AKAK; ALAL-(D)n-ALAL; EBEB-(D)n-EBEB; EKEK-(D)n-EKEK; ELEL-(D)n-ELEL; ABAB-(D)n-ABAB; AKAK-(D)n-AKAK; ALAL-(D)n-ALAL; EBEB-(D)n-EBEB; EKEK-(D)n-EKEK; ELEL-(D)n-ELEL; AABB-(D)n-BBAA; BBAA-(D)n-AABB; AAKK-(D)n-KKAA; AALL-(D)n-LLAA; EEBB-(D)n-BBEE; EEKK-(D)n-KKEE; EELL-(D)n-LLEE; AABB-(D)n-BBAA; AAKK-(D)n-KKAA; AALL-(D)n-LLAA; EEBB-(D)n-BBEE; EEKK-(D)n-KKEE; EELL-(D)n-LLEE; BBB-(D)n-BBA; KKK-(D)n-KKA; LLL-(D)n-LLA; BBB-(D)n-BBE; KKK-(D)n-KKE; LLL-(D)n-LLE; BBB-(D)n-BBA; KKK-(D)n-KKA; LLL-(D)n-LLA; BBB-(D)n-BBE; KKK-(D)n-KKE; LLL-(D)n-LLE; BBB-(D)n-BBA; KKK-(D)n-KKA; LLL-(D)n-LLA; BBB-(D)n-BBE; KKK-(D)n-KKE; LLL-(D)n-LLE; ABBB-(D)n-BBBA; AKKK-(D)n-KKKA; ALLL-(D)n-LLLA; EBBB-(D)n-BBBE; EKKK-(D)n-KKKE; ELLL-(D)n-LLLE; ABBB-(D)n-BBBA; AKKK-(D)n-KKKA; ALLL-(D)n-LLLA; EBBB-(D)n-BBBE; EKKK-(D)n-KKKE; ELLL-(D)n-LLLE; ABBB-(D)n-BBBA; AKKK-(D)n-KKKA; ALLL-(D)n-LLLA; EBBB-(D)n-BBBE; EKKK-(D)n-KKKE; ELLL-(D)n-LLLE; ABBBB-(D)n-BBB; AAKKK-(D)n-KKK; AALLL-(D)n-LLL; EEBBB-(D)n-BBB; EEKKK-(D)n-KKK; EELLL-(D)n-LLL; ABBBB-(D)n-BBB; AAKKK-(D)n-KKK; AALLL-(D)n-LLL; EEBBB-

(D)n-BBB; EEKKK-(D)n-KKK; EELLL-(D)n-LLL; AABBB-(D)n-BBBA; AAKKK-(D)n-KKKA; AALLL-(D)n-LLLA; EEBBB-(D)n-BBBE; EEKKK-(D)n-KKKE; EELLL-(D)n-LLLE; AABBB-(D)n-BBBA; AAKKK-(D)n-KKKA; AALLL-(D)n-LLLA; EEBBB-(D)n-BBBE; EEKKK-(D)n-KKKE; EELLL-(D)n-LLLE; ABBAABB-(D)n-BB; AKKAACK-(D)n-KK; ALLAALLL-(D)n-LL; EBBEEBB-(D)n-BB; EKKEEKK-(D)n-KK; ELLEELL-(D)n-LL; ABBAABB-(D)n-BB; AKKAACK-(D)n-KK; ALLAALLL-(D)n-LL; EBBEEBB-(D)n-BB; EKKEEKK-(D)n-KK; ELLEELL-(D)n-LL; ABBABB-(D)n-BBB; AKKAKK-(D)n-KKK; ALLALLL-(D)n-LLL; EBBEBB-(D)n-BBB; EKKEKK-(D)n-KKK; ELLELL-(D)n-LLL; ABBABB-(D)n-BBB; AKKAKK-(D)n-KKK; ALLALLL-(D)n-LLL; EBBEBB-(D)n-BBB; EKKEKK-(D)n-KKK; ELLELL-(D)n-LLL; EEEK-(D)n-EEEEEEEE; EEK-(D)n-EEEEEEEE; EK-(D)n-EEEEEEEE; EK-(D)n-EEEEKK; K-(D)n-EEEEKEKE; K-(D)n-EEEEKEKEE; K-(D)n-EEKEK; EK-(D)n-EEEEKEKE; EK-(D)n-EEEEKEK; EEK-(D)n-KEEKE; EK-(D)n-EEKEK; EK-(D)n-KEEK; EEK-(D)n-EEEEKEK; EK-(D)n-KEEKEE; EK-(D)n-EEKEKE; EK-(D)n-EEEEKEKE; and EK-(D)n-EEEEKEK;. “A” nucleosides comprise a 2'-modified nucleoside; “B” represents a 2'-4' bicyclic nucleoside; “K” represents a constrained ethyl nucleoside (cEt); “L” represents an LNA nucleoside; and “E” represents a 2'-MOE modified ribonucleoside; “D” represents a 2'-deoxyribonucleoside; “n” represents the length of the gap segment (Y in the 5'-X-Y-Z-3' configuration) and is an integer between 1-20.

[000240] In some embodiments, any one of the gapmers described herein comprises one or more modified internucleoside linkages (e.g., a phosphorothioate linkage) in each of the X, Y, and Z regions. In some embodiments, each internucleoside linkage in the any one of the gapmers described herein is a phosphorothioate linkage. In some embodiments, each of the X, Y, and Z regions independently comprises a mix of phosphorothioate linkages and phosphodiester linkages. In some embodiments, each internucleoside linkage in the gap region Y is a phosphorothioate linkage, the 5' wing region X comprises a mix of phosphorothioate linkages and phosphodiester linkages, and the 3' wing region Z comprises a mix of phosphorothioate linkages and phosphodiester linkages.

[000241] Non-limiting examples of FXN-targeting oligonucleotides are provided in **Table 8**.

Table 8. FXN Targeting Oligonucleotides

ASO ID	Target sequence	SEQ ID NO:	ASO	SEQ ID NO:	Modified ASO:
1	AGAAGAAG AAGAAGAA GAAG	162	CUUCUTCTTCTT CTTCUUCU	165	oC*oU*oU*oC*oU*dT*xC*dT*dT*xC*dT* dT*xC*dT*dT*oC*oU*oU*oC*oU (SEQ ID NO: 165)
2	AAGAAGAA GAAGAAGA AGAA	163	UUCUUCTTCTT CTTCUUCUU	166	oU*oU*oC*oU*oU*xC*dT*dT*xC*dT*dT* xC*dT*dT*xC*oU*oU*oC*oU*oU (SEQ ID NO: 166)

3	GAAGAAGA AGAAGAAG AAGA	164	UCUUCTTCTTCT TCTUCUUC	167	oU*oC*oU*oU*oC*dT*dT*xdC*dT*dT*xdC *dT*dT*xdC*dT*oU*oC*oU*oU*oC (SEQ ID NO: 167)
4	AGAAGAAG AAGAAGAA GAAG	162	CUUCUUCUUCU UCUUCUUCU	168	oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU* oU*oC*oU*oU*oC*oU*oU*oC*oU (SEQ ID NO: 168)
5	AAGAAGAA GAAGAAGA AGAA	163	UUCUUCUUCUU CUUCUUCUU	169	oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU* oC*oU*oU*oC*oU*oU*oC*oU*oU (SEQ ID NO: 169)
6	GAAGAAGA AGAAGAAG AAGA	164	UCUUCUUCUUC UUCUUCUUC	170	oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC* oU*oU*oC*oU*oU*oC*oU*oU*oC (SEQ ID NO: 170)
7	AGAAGAAG AAGAAGAA GAAG	162	CUUCTTCTTCTT CTTCTUCU	171	+C*+U*+U*xdC*dT*dT*xdC*dT*dT*xdC*d T*dT*xdC*dT*dT*xdC*dT*+U*+C*+U (SEQ ID NO: 171)
8	AAGAAGAA GAAGAAGA AGAA	163	UUCTTCTTCTTC TTCTTCUU	172	+U*+U*+C*dT*dT*xdC*dT*dT*xdC*dT*dT* *xdC*dT*dT*xdC*dT*dT*+C*+U*+U (SEQ ID NO: 172)
9	GAAGAAGA AGAAGAAG AAGA	164	UCUTCTTCTTCT TCTTCUUC	173	+U*+C*+U*dT*xdC*dT*dT*xdC*dT*dT*xd C*dT*dT*xdC*dT*dT*xdC*+U*+U*+C (SEQ ID NO: 173)
10	AGAAGAAG AAGAAGAA GAAG	162	CUUCUTCTTCTT CTTCUUCU	165	+C*+U*+U*+C*+U*dT*xdC*dT*dT*xdC*dT *dT*xdC*dT*dT*+C*+U*+U*+C*+U (SEQ ID NO: 165)
11	AAGAAGAA GAAGAAGA AGAA	163	UUCUUCTTCTT CTTCUUCUU	166	+U*+U*+C*+U*+U*xdC*dT*dT*xdC*dT*dT* *xdC*dT*dT*xdC*+U*+U*+C*+U*+U (SEQ ID NO: 166)
12	GAAGAAGA AGAAGAAG AAGA	164	UCUUCTTCTTCT TCTUCUUC	167	+U*+C*+U*+U*+C*dT*dT*xdC*dT*dT*xdC *dT*dT*xdC*dT*+U*+C*+U*+U*+C (SEQ ID NO: 167)
13	AGAAGAAG AAGAAGAA GAAG	162	CUUCUUCUUCU UCUUCUUCU	168	xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC *+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U (SEQ ID NO: 168)
14	AAGAAGAA GAAGAAGA AGAA	163	UUCUUCUUCUU CUUCUUCUU	169	+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U* +U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U (SEQ ID NO: 169)
15	GAAGAAGA AGAAGAAG AAGA	164	UCUUCUUCUUC UUCUUCUUC	170	+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U* xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC (SEQ ID NO: 170)
16	AGAAGAAG AAGAAGAA GAAG	162	CTTCTTCTTCTT CTTCTTCT	174	+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*d T*+C*dT*dT*+C*dT*dT*+C*dT (SEQ ID NO: 174)
17	AAGAAGAA GAAGAAGA AGAA	163	TTCTTCTTCTTC TTCTTCTT	175	dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+ C*dT*dT*+C*dT*dT*+C*dT*dT (SEQ ID NO: 175)
18	GAAGAAGA AGAAGAAG AAGA	164	TCTTCTTCTTCT TCTTCTTC	176	dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*d T*dT*+C*dT*dT*+C*dT*dT*+C (SEQ ID NO: 176)

** The target sequence shown contains Ts. Binding of the oligonucleotides to DNA and/or RNA is contemplated.

“xdC” indicates a 5-methyl-deoxycytidine; “dN” indicates a 2'-deoxyribonucleoside; “+N” indicates a LNA nucleoside; “oN” indicates a 2'- MOE modified ribonucleoside; “oC” indicates a 5-methyl-2'-MOE-cytidine; “+C” indicates a 5-methyl-2'-4'-bicyclic-cytidine (2'-4' methylene bridge); “oU” indicates a 5-methyl-2'-MOE-uridine; “+U” indicates a 5-methyl-2'-4'-bicyclic-uridine (2'-4' methylene bridge); “*” indicates a phosphorothioate internucleoside linkage.

[000242] In some embodiments, an FXN-targeting oligonucleotide described herein is 15-20 nucleosides (e.g., 15, 16, 17, 18, 19, or 20 nucleosides) in length, comprises a region of complementarity to at least 15 consecutive nucleosides (e.g., at least 15, at least 16, at least 17, at least 18, at least 19, or at least 20) of any one of SEQ ID NOs: 162-164, and comprises a 5'-X-Y-Z-3' configuration, wherein X comprises 3-5 (e.g., 3, 4, or 5) linked nucleosides, wherein at least one of the nucleosides in X is a 2'-modified nucleoside (e.g., 2'-MOE modified nucleoside, LNA, cEt, or ENA); Y comprises 6-10 (e.g., 6, 7, 8, 9, or 10) linked 2'-deoxyribonucleosides, wherein each cytidine in Y is optionally and independently a 5-methyl-cytidine; and Z comprises 3-5 (e.g., 3, 4, or 5) linked nucleosides, wherein at least one of the nucleosides in Z is a 2'-modified nucleoside (e.g., 2'-MOE modified nucleoside, 2'-O-Me modified nucleoside, LNA, cEt, or ENA).

[000243] In some embodiments, an FXN-targeting oligonucleotide comprises at least 15 consecutive nucleosides of (e.g., at least 15, at least 16, at least 17, at least 18, at least 19, or at least 20) the nucleotide sequence of any one of SEQ ID NOs: 165-176, and comprises a 5'-X-Y-Z-3' configuration, wherein X comprises 3-5 (e.g., 3, 4, or 5) linked nucleosides, wherein at least one of the nucleosides in X is a 2'-modified nucleoside (e.g., 2'-MOE modified nucleoside, 2'-O-Me modified nucleoside, LNA, cEt, or ENA); Y comprises 6-10 (e.g., 6, 7, 8, 9, or 10) linked 2'-deoxyribonucleosides, wherein each cytidine in Y is optionally and independently a 5-methyl-cytidine; and Z comprises 3-5 (e.g., 3, 4, or 5) linked nucleosides, wherein at least one of the nucleosides in Z is a 2'-modified nucleoside (e.g., 2'-MOE modified nucleoside, 2'-O-Me modified nucleoside, LNA, cEt, or ENA).

[000244] In some embodiments, an FXN-targeting oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 165-176 and comprises a 5'-X-Y-Z-3' configuration, wherein X comprises 3-5 (e.g., 3, 4, or 5) linked nucleosides, wherein at least one of the nucleosides in X is a 2'-modified nucleoside (e.g., 2'-MOE modified nucleoside, 2'-O-Me modified nucleoside, LNA, cEt, or ENA); Y comprises 6-10 (e.g., 6, 7, 8, 9, or 10) linked 2'-deoxyribonucleosides, wherein each cytidine in Y is optionally and independently a 5-methyl-cytidine; and Z comprises 3-5 (e.g., 3, 4, or 5) linked nucleosides, wherein at least one of the nucleosides in Z is a 2'-modified nucleoside (e.g., 2'-MOE modified nucleoside, 2'-O-Me modified nucleoside, LNA, cEt, or ENA).

[000245] In some embodiments, each nucleoside in X is a 2'-modified nucleoside and/or (e.g., and) each nucleoside in Z is a 2'-modified nucleoside. In some embodiments, the 2'-modified nucleoside is a 2'-4' bicyclic nucleoside (e.g., LNA, cEt, or ENA) or a non-bicyclic 2'-modified nucleoside (e.g., 2'-MOE modified nucleoside or 2'-O-Me modified nucleoside).

[000246] In some embodiments, each nucleoside in X is a non-bicyclic 2'-modified nucleoside (e.g., 2'-MOE modified nucleoside) and/or (e.g., and) each nucleoside in Z is a non-bicyclic 2'-modified nucleoside (e.g., 2'-MOE modified nucleoside). In some embodiments, each nucleoside in X is a 2'-4' bicyclic nucleoside (e.g., LNA, cEt, or ENA) and/or (e.g., and) each nucleoside in Z is a 2'-4' bicyclic nucleoside (e.g., LNA, cEt, or ENA).

[000247] In some embodiments, an FXN-targeting oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 165-167 and comprises a 5'-X-Y-Z-3' configuration, wherein X comprises 5 linked nucleosides, wherein each nucleoside in X is a 2'-MOE modified nucleoside; Y comprises 10 linked 2'-deoxyribonucleosides, wherein each cytidine in Y is optionally and independently a 5-methyl-cytidine; and Z comprises 5 linked nucleosides, wherein each nucleoside in Z is a 2'-MOE modified nucleoside.

[000248] In some embodiments, an FXN-targeting oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 165-167 and comprises a 5'-X-Y-Z-3' configuration, wherein X comprises 5 linked nucleosides, wherein each nucleoside in X is a LNA nucleoside; Y comprises 10 linked 2'-deoxyribonucleosides, wherein each cytidine in Y is optionally and independently a 5-methyl-cytidine; and Z comprises 5 linked nucleosides, wherein each nucleoside in Z is a LNA nucleoside.

[000249] In some embodiments, an FXN-targeting oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 171-173 and comprises a 5'-X-Y-Z-3' configuration, wherein X comprises 3 linked nucleosides, wherein each nucleoside in X is a LNA nucleoside; Y comprises 14 linked 2'-deoxyribonucleosides, wherein each cytidine in Y is optionally and independently a 5-methyl-cytidine; and Z comprises 3 linked nucleosides, wherein each nucleoside in Z is a LNA nucleoside.

[000250] In some embodiments, an FXN-targeting oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 168-170, and each nucleoside is a 2'-MOE modified nucleoside.

[000251] In some embodiments, an FXN-targeting oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 168-170, each T in the oligonucleotide is a LNA nucleoside, and each C in the oligonucleotide is a 5-methyl-deoxycytidine.

[000252] In some embodiments, an FXN-targeting oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 174-176, and each C in the oligonucleotide is a LNA nucleoside and each T is a deoxythymidine.

[000253] In some embodiments, in any one of the FXN-targeting oligonucleotides described herein, each cytidine (e.g., a 2'-modified cytidine) in X and/or Z is optionally and

independently a 5-methyl-cytidine, and/or each uridine (e.g., a 2'-modified uridine) in X and/or Z is optionally and independently a 5-methyl-uridine.

[000254] In some embodiments, any one of the FXN-targeting oligonucleotides described herein comprises one or more phosphorothioate internucleoside linkages. In some embodiments, each internucleoside linkage in the FXN-targeting oligonucleotide is a phosphorothioate internucleoside linkage.

[000255] In some embodiments, the FXN-targeting oligonucleotide is selected from modified ASOs 1-18 listed in **Table 8**. In some embodiments, any one of the FXN-targeting oligonucleotides can be in salt form, e.g., as sodium, potassium, or magnesium salts.

[000256] In some embodiments, the 5' or 3' nucleoside (e.g., terminal nucleoside) of any one of the oligonucleotides described herein (e.g., the oligonucleotides listed in **Table 8**) is conjugated to an amine group, optionally via a spacer. In some embodiments, the spacer comprises an aliphatic moiety. In some embodiments, the spacer comprises a polyethylene glycol moiety. In some embodiments, a phosphodiester linkage is present between the spacer and the 5' or 3' nucleoside of the oligonucleotide. In some embodiments, the 5' or 3' nucleoside (e.g., terminal nucleoside) of any of the oligonucleotides described herein (e.g., the oligonucleotides listed in **Table 8**) is conjugated to a spacer that is a substituted or unsubstituted aliphatic, substituted or unsubstituted heteroaliphatic, substituted or unsubstituted carbocyclene, substituted or unsubstituted heterocyclene, substituted or unsubstituted arylene, substituted or unsubstituted heteroarylene, -O-, -N(R^A)-, -S-, -C(=O)-, -C(=O)O-, -C(=O)NR^A-, -NR^AC(=O)-, -NR^AC(=O)R^A-, -C(=O)R^A-, -NR^AC(=O)O-, -NR^AC(=O)N(R^A)-, -OC(=O)-, -OC(=O)O-, -OC(=O)N(R^A)-, -S(O)₂NR^A-, -NR^AS(O)₂-, or a combination thereof; each R^A is independently hydrogen or substituted or unsubstituted alkyl. In certain embodiments, the spacer is a substituted or unsubstituted alkylene, substituted or unsubstituted heterocyclene, substituted or unsubstituted heteroarylene, -O-, -N(R^A)-, or -C(=O)N(R^A)₂, or a combination thereof.

[000257] In some embodiments, the 5' or 3' nucleoside of any one of the oligonucleotides described herein (e.g., the oligonucleotides listed in **Table 8**) is conjugated to a compound of the formula -NH₂-(CH₂)_n-, wherein n is an integer from 1 to 12. In some embodiments, n is 6, 7, 8, 9, 10, 11, or 12. In some embodiments, a phosphodiester linkage is present between the compound of the formula NH₂-(CH₂)_n- and the 5' or 3' nucleoside of the oligonucleotide. In some embodiments, a compound of the formula NH₂-(CH₂)₆- is conjugated to the oligonucleotide via a reaction between 6-amino-1-hexanol (NH₂-(CH₂)₆-OH) and the 5' phosphate of the oligonucleotide.

[000258] In some embodiments, the oligonucleotide is conjugated to a targeting agent, e.g., a muscle targeting agent such as an anti-TfR1 antibody, e.g., via the amine group.

g. RNA Interference (RNAi)

[000259] In some embodiments, the FXN-targeting oligonucleotides provided herein are small interfering RNAs (siRNA), also known as short interfering RNA or silencing RNA. SiRNA, is a class of double-stranded RNA molecules, typically about 20-25 base pairs in length that target nucleic acids (e.g., mRNAs) for degradation via the RNA interference (RNAi) pathway in cells. Specificity of siRNA molecules may be determined by the binding of the antisense strand of the molecule to its target RNA. Effective siRNA molecules are generally less than 30 to 35 base pairs in length to prevent the triggering of non-specific RNA interference pathways in the cell via the interferon response, although longer siRNA can also be effective. In some embodiments, the siRNA molecules are 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 35, 40, 45, 50, or more base pairs in length. In some embodiments, the siRNA molecules are 8 to 30 base pairs in length, 10 to 15 base pairs in length, 10 to 20 base pairs in length, 15 to 25 base pairs in length, 19 to 21 base pairs in length, 21 to 23 base pairs in length.

[000260] Following selection of an appropriate target RNA sequence, siRNA molecules that comprise a nucleotide sequence complementary to all or a portion of the target sequence, i.e., an antisense sequence, can be designed and prepared using appropriate methods (see, e.g., PCT Publication Number WO 2004/016735; and U.S. Patent Publication Nos. 2004/0077574 and 2008/0081791).

[000261] The siRNA molecule can be double stranded (i.e., a dsRNA molecule comprising an antisense strand and a complementary sense strand) or single-stranded (i.e., an ssRNA molecule comprising just an antisense strand). The siRNA molecules can comprise a duplex, asymmetric duplex, hairpin or asymmetric hairpin secondary structure, having self-complementary sense and antisense strands. In some embodiments, the FXN-targeting oligonucleotide described herein is an siRNA comprising an antisense strand and a sense strand.

[000262] In some embodiments, the antisense strand of the siRNA molecule is 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 35, 40, 45, 50, or more nucleotides in length. In some embodiments, the antisense strand is 8 to 50 nucleotides in length, 8 to 40 nucleotides in length, 8 to 30 nucleotides in length, 10 to 15 nucleotides in length, 10 to 20 nucleotides in length, 15 to 25 nucleotides in length, 19 to 21 nucleotides in length, 21 to 23 nucleotides in lengths.

[000263] In some embodiments, the sense strand of the siRNA molecule is 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 35, 40, 45, 50, or more nucleotides in length. In some embodiments, the sense strand is 8 to 50 nucleotides in length, 8 to 40 nucleotides in length, 8 to 30 nucleotides in length, 10 to 15 nucleotides in length, 10 to 20 nucleotides in length, 15 to 25 nucleotides in length, 19 to 21 nucleotides in length, 21 to 23 nucleotides in lengths.

[000264] In some embodiments, siRNA molecules comprise an antisense strand comprising a region of complementarity to a target region in a FXN mRNA. In some embodiments, the region of complementarity is at least 80%, at least 85%, at least 90%, at least 91%, at least 92%, at least 93%, at least 94%, at least 95%, at least 96%, at least 97%, at least 98%, at least 99% or 100% complementary to a target region in a FXN mRNA. In some embodiments, the target region is a region of consecutive nucleotides in the FXN mRNA. In some embodiments, a complementary nucleotide sequence need not be 100% complementary to that of its target to be specifically hybridizable or specific for a target RNA sequence.

[000265] In some embodiments, siRNA molecules comprise an antisense strand that comprises a region of complementarity to a FXN mRNA sequence and the region of complementarity is in the range of 8 to 15, 8 to 30, 8 to 40, or 10 to 50, or 5 to 50, or 5 to 40 nucleotides in length. In some embodiments, a region of complementarity is 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48, 49, or 50 nucleotides in length. In some embodiments, the region of complementarity is complementary with at least 6, at least 7, at least 8, at least 9, at least 10, at least 11, at least 12, at least 13, at least 14, at least 15, at least 16, at least 17, at least 18, at least 19, at least 20, at least 21, at least 22, at least 23, at least 24, at least 25 or more consecutive nucleotides of a FXN mRNA sequence. In some embodiments, the region of complementarity comprises a nucleotide sequence that contains no more than 1, 2, 3, 4, or 5 base mismatches compared to the complementary portion of a FXN mRNA sequence. In some embodiments, the region of complementarity comprises a nucleotide sequence that has up to 3 mismatches over 15 bases, or up to 2 mismatches over 10 bases.

[000266] Double-stranded siRNA may comprise RNA strands that are the same length or different lengths. Double-stranded siRNA molecules can also be assembled from a single oligonucleotide in a stem-loop structure, wherein self-complementary sense and antisense regions of the siRNA molecule are linked by means of a nucleic acid based or non-nucleic acid-based linker(s), as well as circular single-stranded RNA having two or more loop structures and a stem comprising self-complementary sense and antisense strands, wherein the circular RNA can be processed either in vivo or in vitro to generate an active siRNA molecule capable of

mediating RNAi. Small hairpin RNA (shRNA) molecules thus are also contemplated herein. These molecules comprise a specific antisense sequence in addition to the reverse complement (sense) sequence, typically separated by a spacer or loop sequence. Cleavage of the spacer or loop provides a single-stranded RNA molecule and its reverse complement, such that they may anneal to form a dsRNA molecule (optionally with additional processing steps that may result in addition or removal of one, two, three or more nucleotides from the 3' end and/or (e.g., and) the 5' end of either or both strands). A spacer can be of a sufficient length to permit the antisense and sense sequences to anneal and form a double-stranded structure (or stem) prior to cleavage of the spacer (and, optionally, subsequent processing steps that may result in addition or removal of one, two, three, four, or more nucleotides from the 3' end and/or (e.g., and) the 5' end of either or both strands). A spacer sequence may be an unrelated nucleotide sequence that is situated between two complementary nucleotide sequence regions which, when annealed into a double-stranded nucleic acid, comprise a shRNA.

[000267] The overall length of the siRNA molecules can vary from about 14 to about 100 nucleotides depending on the type of siRNA molecule being designed. Generally between about 14 and about 50 of these nucleotides are complementary to the RNA target sequence, i.e. constitute the specific antisense sequence of the siRNA molecule. For example, when the siRNA is a double- or single-stranded siRNA, the length can vary from about 14 to about 50 nucleotides, whereas when the siRNA is a shRNA or circular molecule, the length can vary from about 40 nucleotides to about 100 nucleotides.

[000268] An siRNA molecule may comprise a 3' overhang at one end of the molecule. The other end may be blunt-ended or have also an overhang (5' or 3'). When the siRNA molecule comprises an overhang at both ends of the molecule, the length of the overhangs may be the same or different. In one embodiment, the siRNA molecule of the present disclosure comprises 3' overhangs of about 1 to about 3 (e.g., 1, 2, 3) nucleotides on both ends of the molecule. In some embodiments, the siRNA molecule comprises 3' overhangs of about 1 to about 3 nucleotides on the sense strand. In some embodiments, the siRNA molecule comprises 3' overhangs of about 1 to about 3 (e.g., 1, 2, 3) nucleotides on the antisense strand. In some embodiments, the siRNA molecule comprises 3' overhangs of about 1 to about 3 (e.g., 1, 2, 3) nucleotides on both the sense strand and the antisense strand.

[000269] In some embodiments, the siRNA molecule comprises one or more modified nucleotides (e.g., 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 or more). In some embodiments, the siRNA molecule comprises one or more modified nucleotides and/or (e.g., and) one or more modified internucleoside linkages. In some embodiments, the modified nucleotide is a modified sugar moiety (e.g., a 2' modified nucleotide). In some embodiments, the siRNA molecule comprises

one or more 2' modified nucleotides, e.g., a 2'-deoxy, 2'-fluoro (2'-F), 2'-O-methyl (2'-O-Me), 2'-O-methoxyethyl (2'-MOE), 2'-O-aminopropyl (2'-O-AP), 2'-O-dimethylaminoethyl (2'-O-DMAOE), 2'-O-dimethylaminopropyl (2'-O-DMAP), 2'-O-dimethylaminoethoxyethyl (2'-O-DMAEOE), or 2'-O--N-methylacetamido (2'-O--NMA). In some embodiments, each nucleotide of the siRNA molecule is a modified nucleotide (e.g., a 2'-modified nucleotide). In some embodiments, the siRNA molecule comprises one or more 2'-O-methyl modified nucleotides. In some embodiments, the siRNA molecule comprises one or more 2'-F modified nucleotides. In some embodiments, the siRNA molecule comprises one or more 2'-O-methyl and 2'-F modified nucleotides.

[000270] In some embodiments, the siRNA molecule contains a phosphorothioate or other modified internucleotide linkage. In some embodiments, the siRNA molecule comprises phosphorothioate internucleoside linkages. In some embodiments, the siRNA molecule comprises phosphorothioate internucleoside linkages between at least two nucleotides. In some embodiments, the siRNA molecule comprises phosphorothioate internucleoside linkages between all nucleotides. For example, in some embodiments, the siRNA molecule comprises modified internucleotide linkages at the first, second, and/or (e.g., and) third internucleoside linkage at the 5' or 3' end of the siRNA molecule.

[000271] In some embodiments, the modified internucleotide linkages are phosphorus-containing linkages. In some embodiments, phosphorus-containing linkages that may be used include, but are not limited to, phosphorothioates, chiral phosphorothioates, phosphorodithioates, phosphotriesters, aminoalkylphosphotriesters, methyl and other alkyl phosphonates comprising 3' alkylene phosphonates and chiral phosphonates, phosphinates, phosphoramidates comprising 3'-amino phosphoramidate and aminoalkylphosphoramidates, thionophosphoramidates, thionoalkylphosphonates, thionoalkylphosphotriesters, and boranophosphates having normal 3'-5' linkages, 2'-5' linked analogs of these, and those having inverted polarity wherein the adjacent pairs of nucleoside units are linked 3'-5' to 5'-3' or 2'-5' to 5'-2'; see US patent nos. 3,687,808; 4,469,863; 4,476,301; 5,023,243; 5,177,196; 5,188,897; 5,264,423; 5,276,019; 5,278,302; 5,286,717; 5,321,131; 5,399,676; 5,405,939; 5,453,496; 5,455,233; 5,466,677; 5,476,925; 5,519,126; 5,536,821; 5,541,306; 5,550,111; 5,563,253; 5,571,799; 5,587,361; and 5,625,050.

[000272] Any of the modified chemistries or formats of siRNA molecules described herein can be combined with each other. For example, one, two, three, four, five, or more different types of modifications can be included within the same siRNA molecule.

[000273] In some embodiments, the antisense strand comprises one or more modified nucleosides (e.g., 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 or more). In some embodiments, the antisense strand

comprises one or more modified nucleosides and/or (e.g., and) one or more modified internucleoside linkages. In some embodiments, the modified nucleotide comprises a modified sugar moiety (e.g., a 2' modified nucleotide). In some embodiments, the antisense strand comprises one or more 2' modified nucleosides, e.g., a 2'-deoxy, 2'-fluoro (2'-F), 2'-O-methyl (2'-O-Me), 2'-O-methoxyethyl (2'-MOE), 2'-O-aminopropyl (2'-O-AP), 2'-O-dimethylaminoethyl (2'-O-DMAOE), 2'-O-dimethylaminopropyl (2'-O-DMAP), 2'-O-dimethylaminoethoxyethyl (2'-O-DMAEOE), or 2'-O--N-methylacetamido (2'-O--NMA). In some embodiments, each nucleoside of the antisense strand is a modified nucleoside (e.g., a 2'-modified nucleotide). In some embodiments, the antisense strand comprises one or more 2'-O-methyl modified nucleosides. In some embodiments, the antisense strand comprises one or more 2'-F modified nucleosides. In some embodiments, the antisense strand comprises one or more 2'-O-methyl and 2'-F modified nucleosides.

[000274] In some embodiments, antisense strand contains a phosphorothioate or other modified internucleoside linkage. In some embodiments, the antisense strand comprises phosphorothioate internucleoside linkages. In some embodiments, the antisense strand comprises phosphorothioate internucleoside linkages between at least two nucleosides. In some embodiments, the antisense strand comprises phosphorothioate internucleoside linkages between all nucleosides. For example, in some embodiments, the antisense strand comprises modified internucleoside linkages at the first, second, and/or (e.g., and) third internucleoside linkage at the 5' or 3' end of the siRNA molecule. In some embodiments, the two internucleoside linkages at the 3' end of the antisense strands are phosphorothioate internucleoside linkages.

[000275] In some embodiments, the modified internucleoside linkages are phosphorus-containing linkages. In some embodiments, phosphorus-containing linkages that may be used include, but are not limited to, phosphorothioates, chiral phosphorothioates, phosphorodithioates, phosphotriesters, aminoalkylphosphotriesters, methyl and other alkyl phosphonates comprising 3'-alkylene phosphonates and chiral phosphonates, phosphinates, phosphoramidates comprising 3'-amino phosphoramidate and aminoalkylphosphoramidates, thionophosphoramidates, thionoalkylphosphonates, thionoalkylphosphotriesters, and boranophosphates having normal 3'-5' linkages, 2'-5' linked analogs of these, and those having inverted polarity wherein the adjacent pairs of nucleoside units are linked 3'-5' to 5'-3' or 2'-5' to 5'-2'; see US patent nos. 3,687,808; 4,469,863; 4,476,301; 5,023,243; 5,177,196; 5,188,897; 5,264,423; 5,276,019; 5,278,302; 5,286,717; 5,321,131; 5,399,676; 5,405,939; 5,453,496; 5,455,233; 5,466,677; 5,476,925; 5,519,126; 5,536,821; 5,541,306; 5,550,111; 5,563,253; 5,571,799; 5,587,361; and 5,625,050.

[000276] Any of the modified chemistries or formats of the antisense strand described herein can be combined with each other. For example, one, two, three, four, five, or more different types of modifications can be included within the same antisense strand.

[000277] In some embodiments, the sense strand comprises one or more modified nucleotides (e.g., 1, 2, 3, 4, 5, 6, 7, 8, 9, 10 or more). In some embodiments, the sense strand comprises one or more modified nucleosides and/or (e.g., and) one or more modified internucleoside linkages. In some embodiments, the modified nucleotide is a modified sugar moiety (e.g., a 2' modified nucleoside). In some embodiments, the sense strand comprises one or more 2' modified nucleosides, e.g., a 2'-deoxy, 2'-fluoro (2'-F), 2'-O-methyl (2'-O-Me), 2'-O-methoxyethyl (2'-MOE), 2'-O-aminopropyl (2'-O-AP), 2'-O-dimethylaminoethyl (2'-O-DMAOE), 2'-O-dimethylaminopropyl (2'-O-DMAP), 2'-O-dimethylaminoethoxyethyl (2'-O-DMAEOE), or 2'-O--N-methylacetamido (2'-O--NMA). In some embodiments, each nucleoside of the sense strand is a modified nucleoside (e.g., a 2'-modified nucleotide). In some embodiments, the sense strand comprises one or more phosphorodiamidate morpholinos. In some embodiments, the sense strand is a phosphorodiamidate morpholino oligomer (PMO). In some embodiments, the sense strand comprises one or more 2'-O-methyl modified nucleosides. In some embodiments, the sense strand comprises one or more 2'-F modified nucleosides. In some embodiments, the sense strand comprises one or more 2'-O-methyl and 2'-F modified nucleosides.

[000278] In some embodiments, the sense strand contains a phosphorothioate or other modified internucleoside linkage. In some embodiments, the sense strand comprises phosphorothioate internucleoside linkages. In some embodiments, the sense strand comprises phosphorothioate internucleoside linkages between at least two nucleosides. In some embodiments, the sense strand comprises phosphorothioate internucleoside linkages between all nucleosides. For example, in some embodiments, the sense strand comprises modified internucleotide linkages at the first, second, and/or (e.g., and) third internucleoside linkage at the 5' or 3' end of the sense strand. In some embodiments, the sense strand comprises phosphodiester internucleoside linkage. In some embodiments, the sense strand does not comprise phosphorothioate internucleoside linkage. In some embodiments, the modified internucleotide linkages are phosphorus-containing linkages. In some embodiments, phosphorus-containing linkages that may be used include, but are not limited to, phosphorothioates, chiral phosphorothioates, phosphorodithioates, phosphotriesters, aminoalkylphosphotriesters, methyl and other alkyl phosphonates comprising 3'-alkylene phosphonates and chiral phosphonates, phosphinates, phosphoramidates comprising 3'-amino phosphoramidate and aminoalkylphosphoramidates, thionophosphoramidates,

thionoalkylphosphonates, thionoalkylphosphotriesters, and boranophosphates having normal 3'-5' linkages, 2'-5' linked analogs of these, and those having inverted polarity wherein the adjacent pairs of nucleoside units are linked 3'-5' to 5'-3' or 2'-5' to 5'-2'; see US patent nos. 3,687,808; 4,469,863; 4,476,301; 5,023,243; 5,177,196; 5,188,897; 5,264,423; 5,276,019; 5,278,302; 5,286,717; 5,321,131; 5,399,676; 5,405,939; 5,453,496; 5,455,233; 5,466,677; 5,476,925; 5,519,126; 5,536,821; 5,541,306; 5,550,111; 5,563,253; 5,571,799; 5,587,361; and 5,625,050.

[000279] Any of the modified chemistries or formats of the sense strand described herein can be combined with each other. For example, one, two, three, four, five, or more different types of modifications can be included within the same sense strand.

[000280] In some embodiments, the antisense or sense strand of the siRNA molecule comprises modifications that enhance or reduce RNA-induced silencing complex (RISC) loading. In some embodiments, the antisense strand of the siRNA molecule comprises modifications that enhance RISC loading. In some embodiments, the sense strand of the siRNA molecule comprises modifications that reduce RISC loading and reduce off-target effects. In some embodiments, the antisense strand of the siRNA molecule comprises a 2'-methoxyethyl (2'-MOE) modification. The addition of the 2'-methoxyethyl (2'-MOE) group at the cleavage site improves both the specificity and silencing activity of siRNAs by facilitating the oriented RNA-induced silencing complex (RISC) loading of the modified strand, as described in Song et al., (2017) *Mol Ther Nucleic Acids* 9:242-250, incorporated herein by reference in its entirety. In some embodiments, the antisense strand of the siRNA molecule comprises a 2'-O-Me-phosphorodithioate modification, which increases RISC loading as described in Wu et al., (2014) *Nat Commun* 5:3459, incorporated herein by reference in its entirety.

[000281] In some embodiments, the sense strand of the siRNA molecule comprises a 5'-morpholino, which reduces RISC loading of the sense strand and improves antisense strand selection and RNAi activity, as described in Kumar et al., (2019) *Chem Commun (Camb)* 55(35):5139-5142, incorporated herein by reference in its entirety. In some embodiments, the sense strand of the siRNA molecule is modified with a synthetic RNA-like high affinity nucleotide analogue, Locked Nucleic Acid (LNA), which reduces RISC loading of the sense strand and further enhances antisense strand incorporation into RISC, as described in Elman et al., (2005) *Nucleic Acids Res.* 33(1): 439-447, incorporated herein by reference in its entirety. In some embodiments, the sense strand of the siRNA molecule comprises a 5' unlocked nucleic acid (UNA) modification, which reduce RISC loading of the sense strand and improve silencing potency of the antisense strand, as described in Snead et al., (2013) *Mol Ther Nucleic Acids* 2(7):e103, incorporated herein by reference in its entirety. In some embodiments, the sense strand of the siRNA molecule comprises a 5-nitroindole modification, which decreases the

RNAi potency of the sense strand and reduces off-target effects as described in Zhang et al., (2012) *Chembiochem* 13(13):1940-1945, incorporated herein by reference in its entirety. In some embodiments, the sense strand comprises a 2'-O-methyl (2'-O-Me) modification, which reduces RISC loading and the off-target effects of the sense strand, as described in Zheng et al., *FASEB* (2013) 27(10): 4017-4026, incorporated herein by reference in its entirety. In some embodiments, the sense strand of the siRNA molecule is fully substituted with morpholino, 2'-MOE or 2'-O-Me residues, and are not recognized by RISC as described in Kole et al., (2012) *Nature reviews. Drug Discovery* 11(2):125-140, incorporated herein by reference in its entirety. In some embodiments the antisense strand of the siRNA molecule comprises a MOE modification and the sense strand comprises a 2'-O-Me modification (see e.g., Song et al., (2017) *Mol Ther Nucleic Acids* 9:242-250). In some embodiments at least one (e.g., at least 2, at least 3, at least 4, at least 5, at least 10) siRNA molecule is linked (e.g., covalently) to a muscle-targeting agent. In some embodiments, the muscle-targeting agent may comprise, or consist of, a nucleic acid (e.g., DNA or RNA), a peptide (e.g., an antibody), a lipid (e.g., a microvesicle), or a sugar moiety (e.g., a polysaccharide). In some embodiments, the muscle-targeting agent is an antibody. In some embodiments, the muscle-targeting agent is an anti-transferrin receptor antibody (e.g., any one of the anti-TfR1 antibodies provided in Tables 2-7). In some embodiments, the muscle-targeting agent may be covalently linked to the 5' end of the sense strand of the siRNA molecule. In some embodiments, the muscle-targeting agent may be covalently linked to the 3' end of the sense strand of the siRNA molecule. In some embodiments, the muscle-targeting agent may be covalently linked internally to the sense strand of the siRNA molecule. In some embodiments, the muscle-targeting agent may be covalently linked to the 5' end of the antisense strand of the siRNA molecule. In some embodiments, the muscle-targeting agent may be covalently linked to the 3' end of the antisense strand of the siRNA molecule. In some embodiments, the muscle-targeting agent may be covalently linked internally to the antisense strand of the siRNA molecule.

C. Linkers

[000282] Complexes described herein generally comprise a linker that covalently links any one of the anti-TfR1 antibodies described herein to a molecular payload. A linker comprises at least one covalent bond. In some embodiments, a linker may be a single bond, e.g., a disulfide bond or disulfide bridge, that covalently links an anti-TfR1 antibody to a molecular payload. However, in some embodiments, a linker may covalently link any one of the anti-TfR1 antibodies described herein to a molecular payload through multiple covalent bonds. In some embodiments, a linker may be a cleavable linker. However, in some embodiments, a linker may

be a non-cleavable linker. A linker is typically stable *in vitro* and *in vivo*, and may be stable in certain cellular environments. Additionally, typically a linker does not negatively impact the functional properties of either the anti-TfR1 antibody or the molecular payload. Examples and methods of synthesis of linkers are known in the art (see, e.g., Kline, T. et al. “Methods to Make Homogenous Antibody Drug Conjugates.” *Pharmaceutical Research*, 2015, 32:11, 3480–3493.; Jain, N. et al. “Current ADC Linker Chemistry” *Pharm Res.* 2015, 32:11, 3526–3540.; McCombs, J.R. and Owen, S.C. “Antibody Drug Conjugates: Design and Selection of Linker, Payload and Conjugation Chemistry” *AAPS J.* 2015, 17:2, 339–351.).

[000283] A linker typically will contain two different reactive species that allow for attachment to both the anti-TfR1 antibody and a molecular payload. In some embodiments, the two different reactive species may be a nucleophile and/or an electrophile. In some embodiments, a linker contains two different electrophiles or nucleophiles that are specific for two different nucleophiles or electrophiles. In some embodiments, a linker is covalently linked to an anti-TfR1 antibody via conjugation to a lysine residue or a cysteine residue of the anti-TfR1 antibody. In some embodiments, a linker is covalently linked to a cysteine residue of an anti-TfR1 antibody via a maleimide-containing linker, wherein optionally the maleimide-containing linker comprises a maleimidocaproyl or maleimidomethyl cyclohexane-1-carboxylate group. In some embodiments, a linker is covalently linked to a cysteine residue of an anti-TfR1 antibody or thiol functionalized molecular payload via a 3-arylpropionitrile functional group. In some embodiments, a linker is covalently linked to a lysine residue of an anti-TfR1 antibody. In some embodiments, a linker is covalently linked to an anti-TfR1 antibody and/or (e.g., and) a molecular payload, independently, via an amide bond, a carbamate bond, a hydrazide, a triazol, a thioether, and/or a disulfide bond.

i. Cleavable Linkers

[000284] A cleavable linker may be a protease-sensitive linker, a pH-sensitive linker, or a glutathione-sensitive linker. These linkers are typically cleavable only intracellularly and are preferably stable in extracellular environments, e.g., extracellular to a muscle cell.

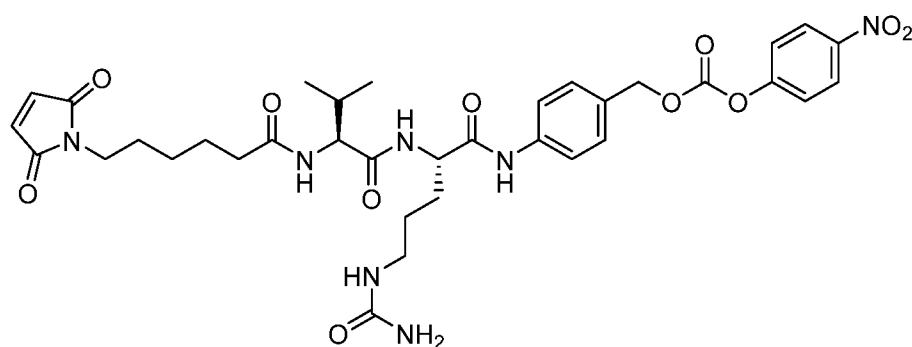
[000285] Protease-sensitive linkers are cleavable by protease enzymatic activity. These linkers typically comprise peptide sequences and may be 2-10 amino acids, about 2-5 amino acids, about 5-10 amino acids, about 10 amino acids, about 5 amino acids, about 3 amino acids, or about 2 amino acids in length. In some embodiments, a peptide sequence may comprise naturally occurring amino acids, e.g., cysteine, alanine, or non-naturally occurring or modified amino acids. Non-naturally occurring amino acids include β -amino acids, homo-amino acids, proline derivatives, 3-substituted alanine derivatives, linear core amino acids, N-methyl amino acids, and others known in the art. In some embodiments, a protease-sensitive linker comprises

a valine-citrulline or alanine-citrulline sequence. In some embodiments, a protease-sensitive linker can be cleaved by a lysosomal protease, e.g., cathepsin B, and/or (e.g., and) an endosomal protease.

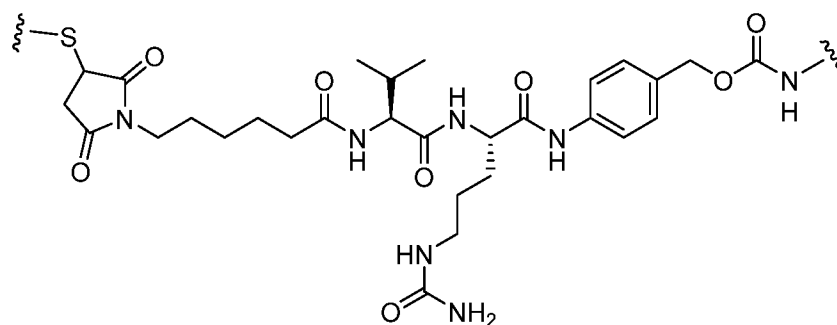
[000286] A pH-sensitive linker is a covalent linkage that readily degrades in high or low pH environments. In some embodiments, a pH-sensitive linker may be cleaved at a pH in a range of 4 to 6. In some embodiments, a pH-sensitive linker comprises a hydrazone or cyclic acetal. In some embodiments, a pH-sensitive linker is cleaved within an endosome or a lysosome.

[000287] In some embodiments, a glutathione-sensitive linker comprises a disulfide moiety. In some embodiments, a glutathione-sensitive linker is cleaved by a disulfide exchange reaction with a glutathione species inside a cell. In some embodiments, the disulfide moiety further comprises at least one amino acid, e.g., a cysteine residue.

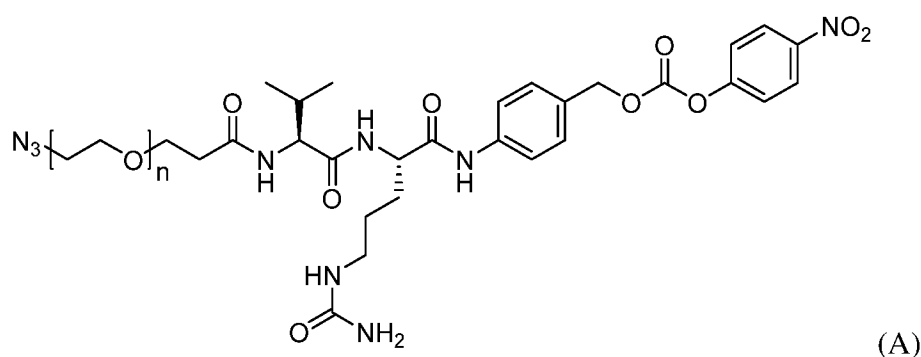
[000288] In some embodiments, a linker comprises a valine-citrulline sequence (e.g., as described in US Patent 6,214,345, incorporated herein by reference). In some embodiments, before conjugation, a linker comprises a structure of:



[000289] In some embodiments, after conjugation, a linker comprises a structure of:

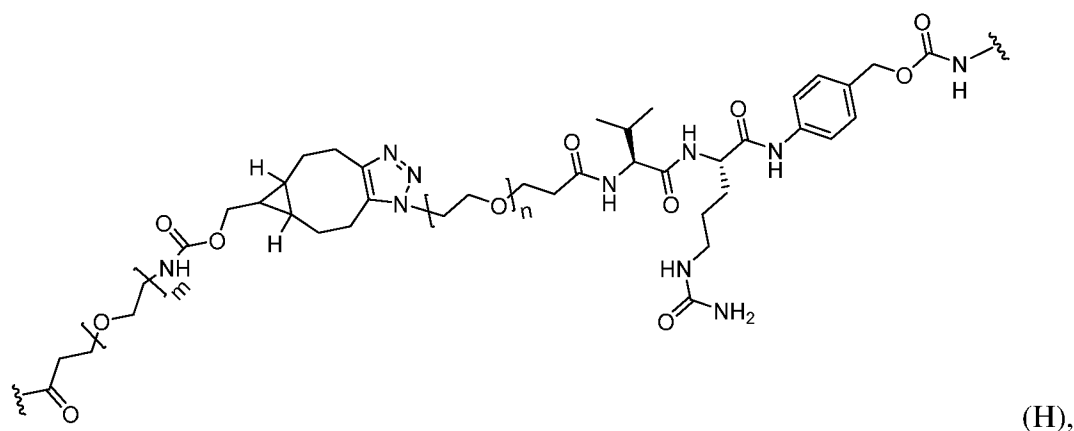


[000290] In some embodiments, before conjugation, a linker comprises a structure of:



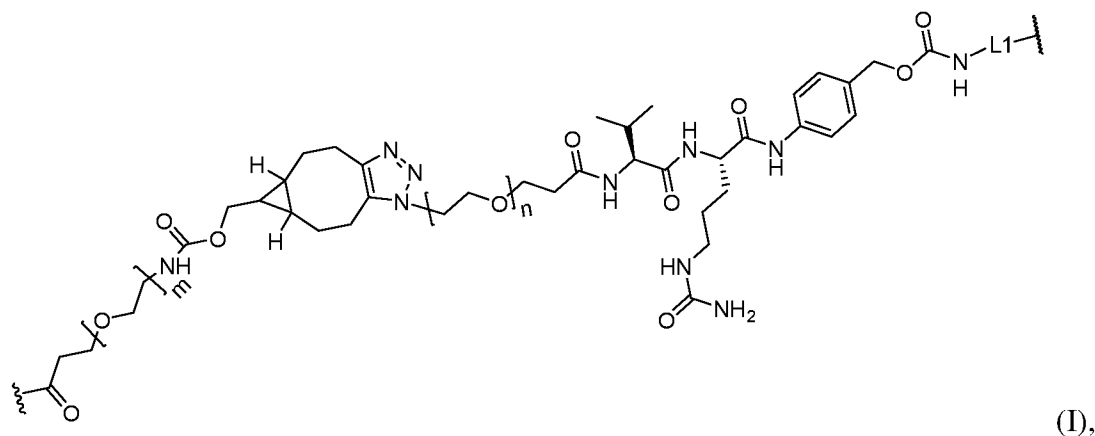
wherein n is any number from 0-10. In some embodiments, n is 3.

[000291] In some embodiments, a linker comprises a structure of:



wherein n is any number from 0-10, wherein m is any number from 0-10. In some embodiments, n is 3 and/or (e.g., and) m is 4.

[000292] In some embodiments, a linker comprises a structure of:



wherein n is any number from 0-10, wherein m is any number from 0-10. In some embodiments, n is 3 and/or (e.g., and) m is 4.

ii. Non-cleavable Linkers

[000293] In some embodiments, non-cleavable linkers may be used. Generally, a non-cleavable linker cannot be readily degraded in a cellular or physiological environment. In some embodiments, a non-cleavable linker comprises an optionally substituted alkyl group, wherein the substitutions may include halogens, hydroxyl groups, oxygen species, and other common

substitutions. In some embodiments, a linker may comprise an optionally substituted alkyl, an optionally substituted alkylene, an optionally substituted arylene, a heteroarylene, a peptide sequence comprising at least one non-natural amino acid, a truncated glycan, a sugar or sugars that cannot be enzymatically degraded, an azide, an alkyne-azide, a peptide sequence comprising a LPXT sequence, a thioether, a biotin, a biphenyl, repeating units of polyethylene glycol or equivalent compounds, acid esters, acid amides, sulfamides, and/or an alkoxy-amine linker. In some embodiments, sortase-mediated ligation can be utilized to covalently link an anti-TfR1 antibody comprising a LPXT sequence to a molecular payload comprising a (G)_n sequence (see, e.g., Proft T. Sortase-mediated protein ligation: an emerging biotechnology tool for protein modification and immobilization. *Biotechnol Lett.* 2010, 32(1):1-10.).

[000294] In some embodiments, a linker may comprise a substituted alkylene, an optionally substituted alkenylene, an optionally substituted alkynylene, an optionally substituted cycloalkylene, an optionally substituted cycloalkenylene, an optionally substituted arylene, an optionally substituted heteroarylene further comprising at least one heteroatom selected from N, O, and S.; an optionally substituted heterocyclylene further comprising at least one heteroatom selected from N, O, and S, an imino, an optionally substituted nitrogen species, an optionally substituted oxygen species O, an optionally substituted sulfur species, or a poly(alkylene oxide), e.g. polyethylene oxide or polypropylene oxide. In some embodiments, a linker may be a non-cleavable N-gamma-maleimidobutyryl-oxysuccinimide ester (GMBS) linker.

iii. Linker conjugation

[000295] In some embodiments, a linker is covalently linked to an anti-TfR1 antibody and/or (e.g., and) molecular payload via a phosphate, thioether, ether, carbon-carbon, carbamate, or amide bond. In some embodiments, a linker is covalently linked to an oligonucleotide through a phosphate or phosphorothioate group, e.g., a terminal phosphate of an oligonucleotide backbone. In some embodiments, a linker is covalently linked to an anti-TfR1 antibody, through a lysine or cysteine residue present on the anti-TfR1 antibody.

[000296] In some embodiments, a linker, or a portion thereof is covalently linked to an anti-TfR1 antibody and/or (e.g., and) molecular payload by a cycloaddition reaction between an azide and an alkyne to form a triazole, wherein the azide or the alkyne may be located on the anti-TfR1 antibody, molecular payload, or the linker. In some embodiments, an alkyne may be a cyclic alkyne, e.g., a cyclooctyne. In some embodiments, an alkyne may be bicyclononyne (also known as bicyclo[6.1.0]nonyne or BCN) or substituted bicyclononyne. In some embodiments, a cyclooctane is as described in International Patent Application Publication WO2011136645, published on November 3, 2011, entitled, “*Fused Cyclooctyne Compounds And Their Use In*

Metal-free Click Reactions". In some embodiments, an azide may be a sugar or carbohydrate molecule that comprises an azide. In some embodiments, an azide may be 6-azido-6-deoxygalactose or 6-azido-N-acetylgalactosamine. In some embodiments, a sugar or carbohydrate molecule that comprises an azide is as described in International Patent Application Publication WO2016170186, published on October 27, 2016, entitled, "*Process For The Modification Of A Glycoprotein Using A Glycosyltransferase That Is Or Is Derived From A $\beta(1,4)$ -N-Acetylgalactosaminyltransferase*". In some embodiments, a cycloaddition reaction between an azide and an alkyne to form a triazole, wherein the azide or the alkyne may be located on the anti-TfR1 antibody, molecular payload, or the linker is as described in International Patent Application Publication WO2014065661, published on May 1, 2014, entitled, "*Modified antibody, antibody-conjugate and process for the preparation thereof*"; or International Patent Application Publication WO2016170186, published on October 27, 2016, entitled, "*Process For The Modification Of A Glycoprotein Using A Glycosyltransferase That Is Or Is Derived From A $\beta(1,4)$ -N-Acetylgalactosaminyltransferase*".

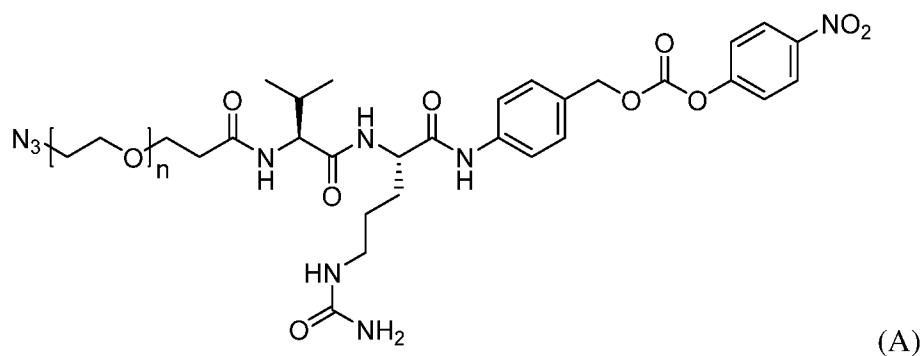
[000297] In some embodiments, a linker comprises a spacer, *e.g.*, a polyethylene glycol spacer or an acyl/carbomoyl sulfamide spacer, *e.g.*, a HydraSpaceTM spacer. In some embodiments, a spacer is as described in Verkade, J.M.M. et al., "*A Polar Sulfamide Spacer Significantly Enhances the Manufacturability, Stability, and Therapeutic Index of Antibody-Drug Conjugates*", *Antibodies*, 2018, 7, 12.

[000298] In some embodiments, a linker is covalently linked to an anti-TfR1 antibody and/or (*e.g.*, and) molecular payload by the Diels-Alder reaction between a dienophile and a diene/hetero-diene, wherein the dienophile or the diene/hetero-diene may be located on the anti-TfR1 antibody, molecular payload, or the linker. In some embodiments a linker is covalently linked to an anti-TfR1 antibody and/or (*e.g.*, and) molecular payload by other pericyclic reactions such as an ene reaction. In some embodiments, a linker is covalently linked to an anti-TfR1 antibody and/or (*e.g.*, and) molecular payload by an amide, thioamide, or sulfonamide bond reaction. In some embodiments, a linker is covalently linked to an anti-TfR1 antibody and/or (*e.g.*, and) molecular payload by a condensation reaction to form an oxime, hydrazone, or semicarbazide group existing between the linker and the anti-TfR1 antibody and/or (*e.g.*, and) molecular payload.

[000299] In some embodiments, a linker is covalently linked to an anti-TfR1 antibody and/or (*e.g.*, and) molecular payload by a conjugate addition reaction between a nucleophile, *e.g.*, an amine or a hydroxyl group, and an electrophile, *e.g.*, a carboxylic acid, carbonate, or an aldehyde. In some embodiments, a nucleophile may exist on a linker and an electrophile may exist on an anti-TfR1 antibody or molecular payload prior to a reaction between a linker and an

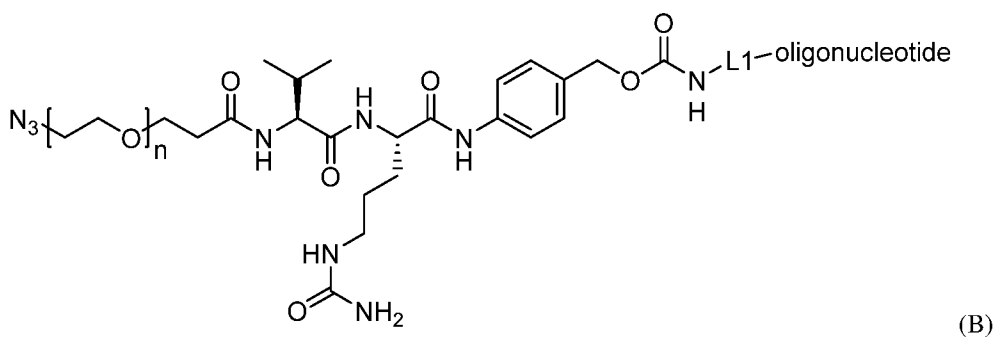
anti-TfR1 antibody or molecular payload. In some embodiments, an electrophile may exist on a linker and a nucleophile may exist on an anti-TfR1 antibody or molecular payload prior to a reaction between a linker and an anti-TfR1 antibody or molecular payload. In some embodiments, an electrophile may be an azide, pentafluorophenyl, a silicon centers, a carbonyl, a carboxylic acid, an anhydride, an isocyanate, a thioisocyanate, a succinimidyl ester, a sulfosuccinimidyl ester, a maleimide, an alkyl halide, an alkyl pseudohalide, an epoxide, an episulfide, an aziridine, an aryl, an activated phosphorus center, and/or an activated sulfur center. In some embodiments, a nucleophile may be an optionally substituted alkene, an optionally substituted alkyne, an optionally substituted aryl, an optionally substituted heterocyclyl, a hydroxyl group, an amino group, an alkylamino group, an anilido group, and/or a thiol group.

[000300] In some embodiments, a linker comprises a valine-citrulline sequence covalently linked to a reactive chemical moiety (e.g., an azide moiety or a BCN moiety for click chemistry). In some embodiments, a linker comprising a valine-citrulline sequence covalently linked to a reactive chemical moiety (e.g., an azide moiety for click chemistry) comprises a structure of:



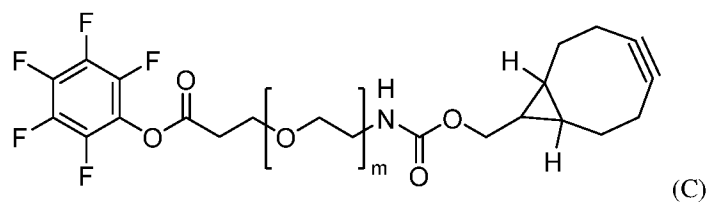
wherein n is any number from 0-10. In some embodiments, n is 3.

[000301] In some embodiments, a linker comprising the structure of Formula (A) is covalently linked (e.g., optionally via additional chemical moieties) to a molecular payload (e.g., an oligonucleotide). In some embodiments, a linker comprising the structure of Formula (A) is covalently linked to an oligonucleotide, e.g., through a nucleophilic substitution with amine-L1-oligonucleotides forming a carbamate bond, yielding a compound comprising a structure of:



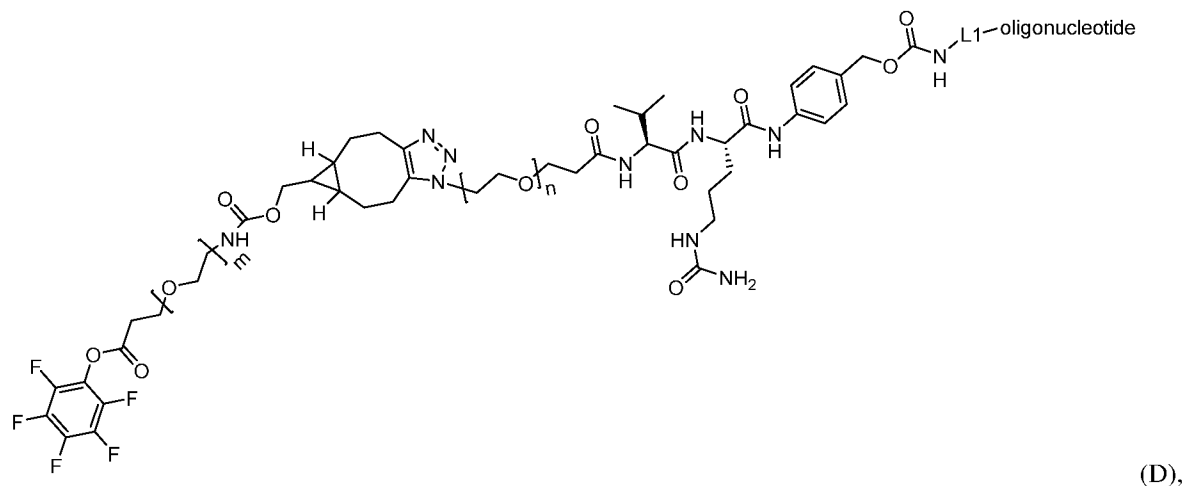
wherein n is any number from 0-10. In some embodiments, n is 3.

[000302] In some embodiments, the compound of Formula (B) is further covalently linked via a triazole to additional moieties, wherein the triazole is formed by a click reaction between the azide of Formula (A) or Formula (B) and an alkyne provided on a bicyclononyne. In some embodiments, a compound comprising a bicyclononyne comprises a structure of:



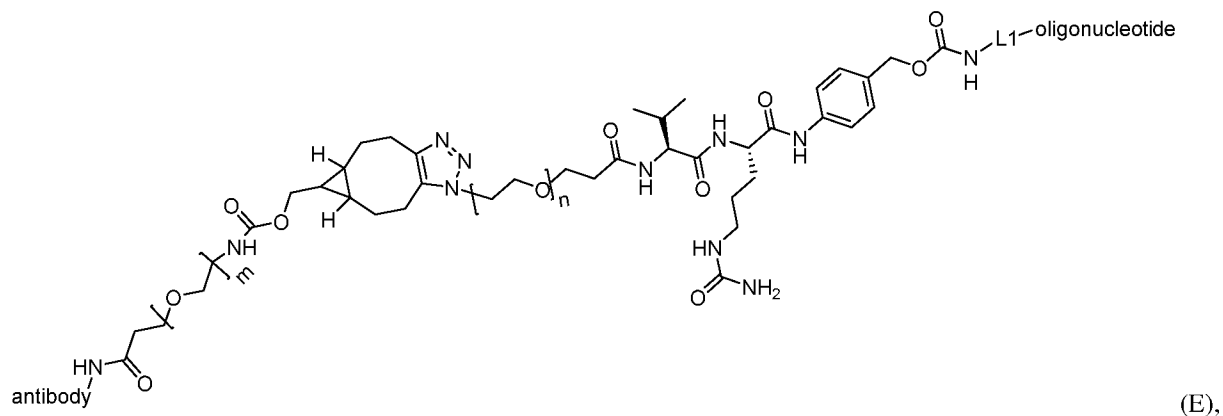
wherein m is any number from 0-10. In some embodiments, m is 4.

[000303] In some embodiments, the azide of the compound of structure (B) forms a triazole via a click reaction with the alkyne of the compound of structure (C), forming a compound comprising a structure of:



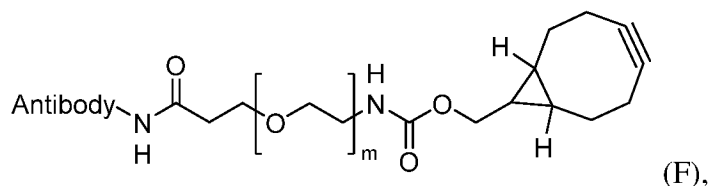
wherein n is any number from 0-10, and wherein m is any number from 0-10. In some embodiments, n is 3 and m is 4.

[000304] In some embodiments, the compound of structure (D) is further covalently linked to a lysine of the anti-TfR1 antibody, forming a complex comprising a structure of:



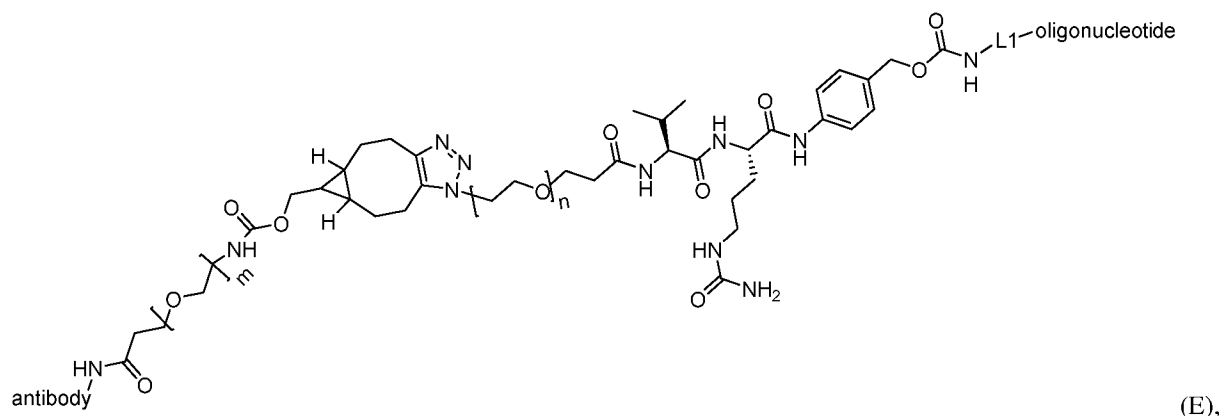
wherein n is any number from 0-10, wherein m is any number from 0-10. In some embodiments, n is 3 and/or (e.g., and) m is 4. It should be understood that the amide shown adjacent the anti-TfR1 antibody in Formula (E) results from a reaction with an amine of the anti-TfR1 antibody, such as a lysine epsilon amine.

[000305] In some embodiments, the compound of Formula (C) is further covalently linked to a lysine of the anti-TfR1 antibody, forming a compound comprising a structure of:



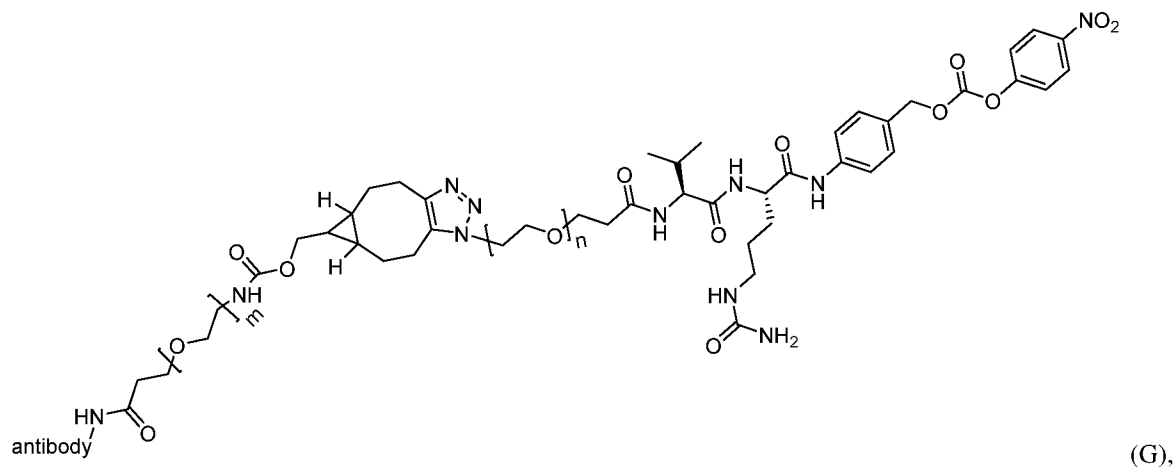
wherein m is 0-15 (e.g., 4). It should be understood that the amide shown adjacent the anti-TfR1 antibody in Formula (F) results from a reaction with an amine of the anti-TfR1 antibody, such as a lysine epsilon amine.

[000306] In some embodiments, the azide of the compound of structure (B) forms a triazole via a click reaction with the alkyne of the compound of structure (F), forming a complex comprising a structure of:



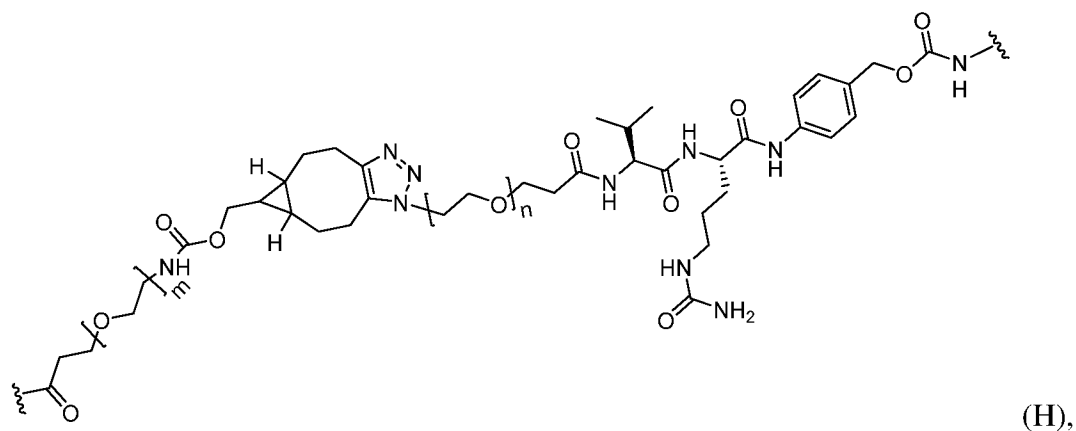
wherein n is any number from 0-10, wherein m is any number from 0-10. In some embodiments, n is 3 and/or (e.g., and) m is 4. It should be understood that the amide shown adjacent the anti-TfR1 antibody in Formula (E) results from a reaction with an amine of the anti-TfR1 antibody, such as a lysine epsilon amine.

[000307] In some embodiments, the azide of the compound of structure (A) forms a triazole via a click reaction with the alkyne of the compound of structure (F), forming a compound comprising: a structure of:



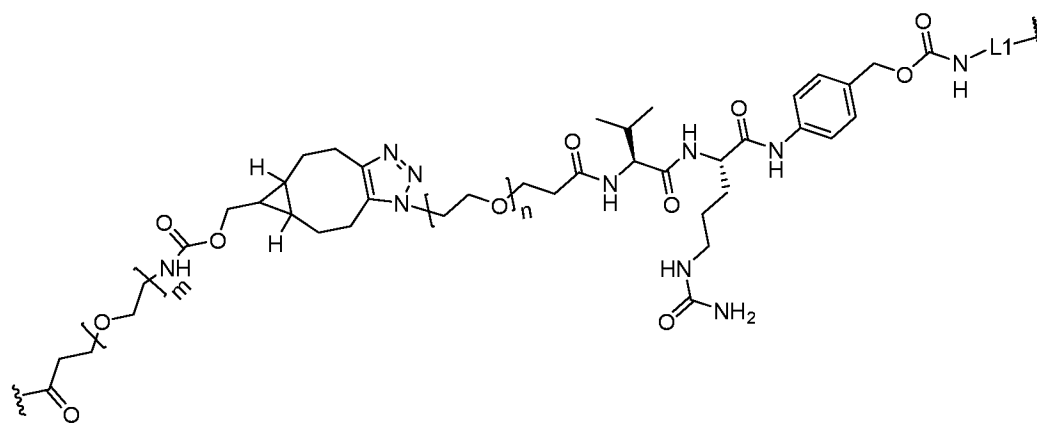
wherein n is any number from 0-10, wherein m is any number from 0-10. In some embodiments, n is 3 and/or (e.g., and) m is 4. In some embodiments, an oligonucleotide is covalently linked to a compound comprising a structure of formula (G), thereby forming a complex comprising a structure of formula (E). It should be understood that the amide shown adjacent the anti-TfR1 antibody in Formula (G) results from a reaction with an amine of the anti-TfR1 antibody, such as a lysine epsilon amine.

[000308] In some embodiments, in any one of the complexes described herein, the anti-TfR1 antibody is covalently linked via a lysine of the anti-TfR1 antibody to a molecular payload (e.g., an oligonucleotide) via a linker comprising a structure of:



wherein n is any number from 0-10, wherein m is any number from 0-10. In some embodiments, n is 3 and/or (e.g., and) m is 4.

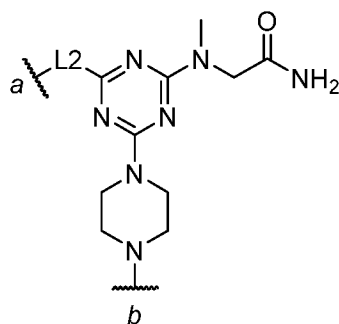
[000309] In some embodiments, in any one of the complexes described herein, the anti-TfR1 antibody is covalently linked via a lysine of the anti-TfR1 antibody to a molecular payload (e.g., an oligonucleotide) via a linker comprising a structure of:



(I),

wherein *n* is any number from 0-10, wherein *m* is any number from 0-10. In some embodiments, *n* is 3 and/or (e.g., and) *m* is 4.

[000310] In some embodiments, in formulae (B), (D), (E), and (I), *L1* is a spacer that is a substituted or unsubstituted aliphatic, substituted or unsubstituted heteroaliphatic, substituted or unsubstituted carbocyclylene, substituted or unsubstituted heterocyclylene, substituted or unsubstituted arylene, substituted or unsubstituted heteroarylene, -O-, -N(R^A)-, -S-, -C(=O)-, -C(=O)O-, -C(=O)NR^A-, -NR^AC(=O)-, -NR^AC(=O)R^A-, -C(=O)R^A-, -NR^AC(=O)O-, -NR^AC(=O)N(R^A)-, -OC(=O)-, -OC(=O)O-, -OC(=O)N(R^A)-, -S(O)₂NR^A-, -NR^AS(O)₂-, or a combination thereof, wherein each R^A is independently hydrogen or substituted or unsubstituted alkyl. In some embodiments, *L1* is



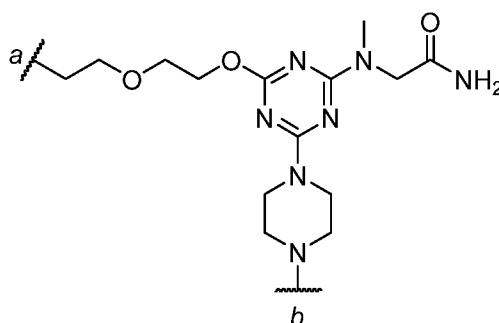
wherein *L2* is

The list of chemical structures for *L2* includes:

- Four structures showing different polyether chains with carbamate groups, each with a different number of repeating units.
- Four structures showing different polyether chains with carbamate groups, each with a different number of repeating units.
- Four structures showing different polyether chains with carbamate groups, each with a different number of repeating units.
- Four structures showing different polyether chains with carbamate groups, each with a different number of repeating units.

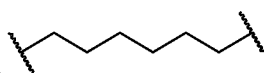
; wherein *a* labels the site directly linked to the carbamate moiety of formulae (B), (D), (E), and (I); and *b* labels the site covalently linked (directly or via additional chemical moieties) to the oligonucleotide.

[000311] In some embodiments, *L1* is:



wherein *a* labels the site directly linked to the carbamate moiety of formulae (B), (D), (E), and (I); and *b* labels the site covalently linked (directly or via additional chemical moieties) to the oligonucleotide.

[000312] In some embodiments, L1 is



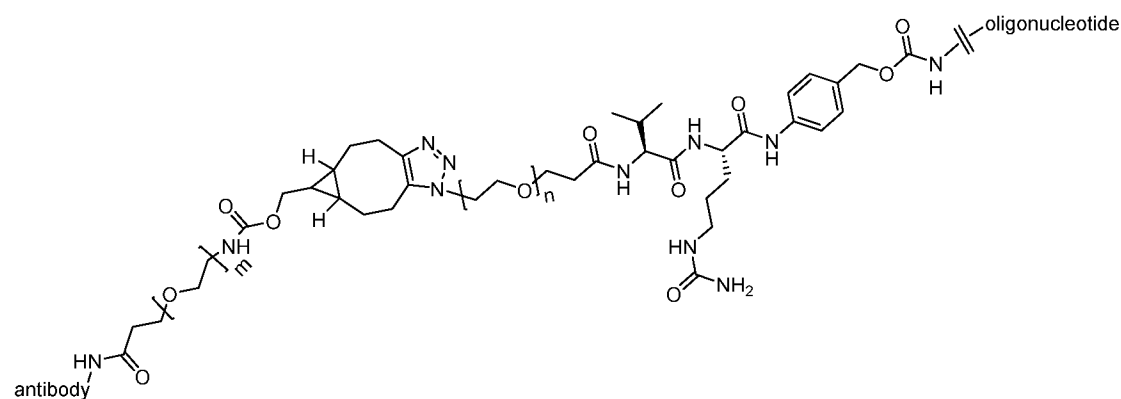
[000313] In some embodiments, L1 is linked to a 5' phosphate of the oligonucleotide. In some embodiments, L1 is linked to a 5' phosphorothioate of the oligonucleotide. In some embodiments, L1 is linked to a 5' phosphonoamidate of the oligonucleotide.

[000314] In some embodiments, L1 is linked to a 5' phosphate of the oligonucleotide. In some embodiments, the linkage of L1 to a 5' phosphate of the oligonucleotide forms a phosphodiester bond between L1 and the oligonucleotide.

[000315] In some embodiments, L1 is linked to a 3' phosphate of the oligonucleotide. In some embodiments, the linkage of L1 to a 3' phosphate of the oligonucleotide forms a phosphodiester bond between L1 and the oligonucleotide.

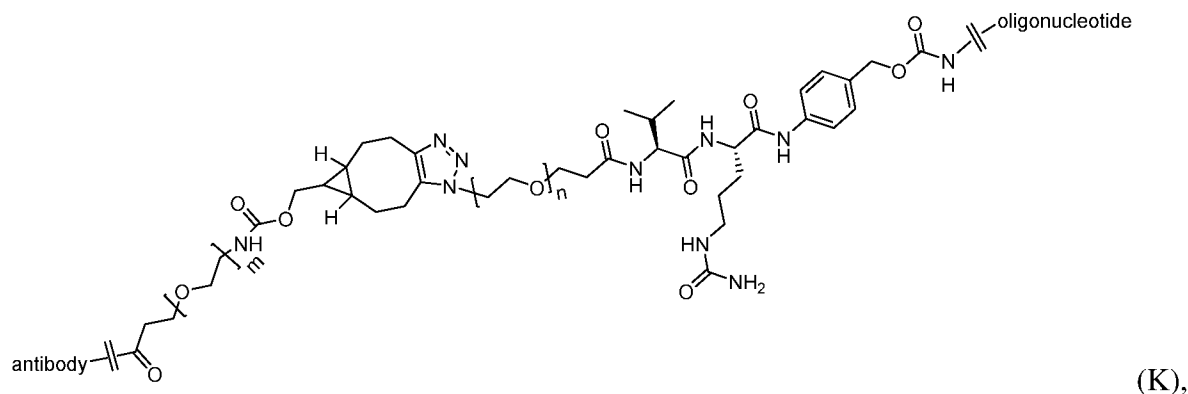
[000316] In some embodiments, L1 is optional (e.g., need not be present).

[000317] In some embodiments, any one of the complexes described herein has a structure of:



wherein *n* is 0-15 (e.g., 3) and *m* is 0-15 (e.g., 4). It should be understood that the amide shown adjacent the anti-TfR1 antibody in Formula (J) results from a reaction with an amine of the anti-TfR1 antibody, such as a lysine epsilon amine.

[000318] In some embodiments, any one of the complexes described herein has a structure of:



wherein n is 0-15 (e.g., 3) and m is 0-15 (e.g., 4).

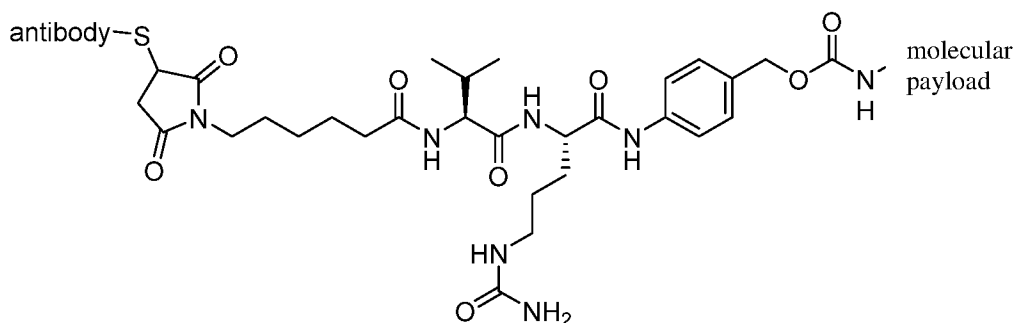
[000319] In some embodiments, the oligonucleotide is modified to comprise an amine group at the 5' end, the 3' end, or internally (e.g., as an amine functionalized nucleobase), prior to linking to a compound, e.g., a compound of formula (A) or formula (G).

[000320] Although linker conjugation is described in the context of anti-TfR1 antibodies and oligonucleotide molecular payloads, it should be understood that use of such linker conjugation on other muscle-targeting agents, such as other muscle-targeting antibodies, and/or on other molecular payloads is contemplated.

D. Examples of Antibody-Molecular Payload Complexes

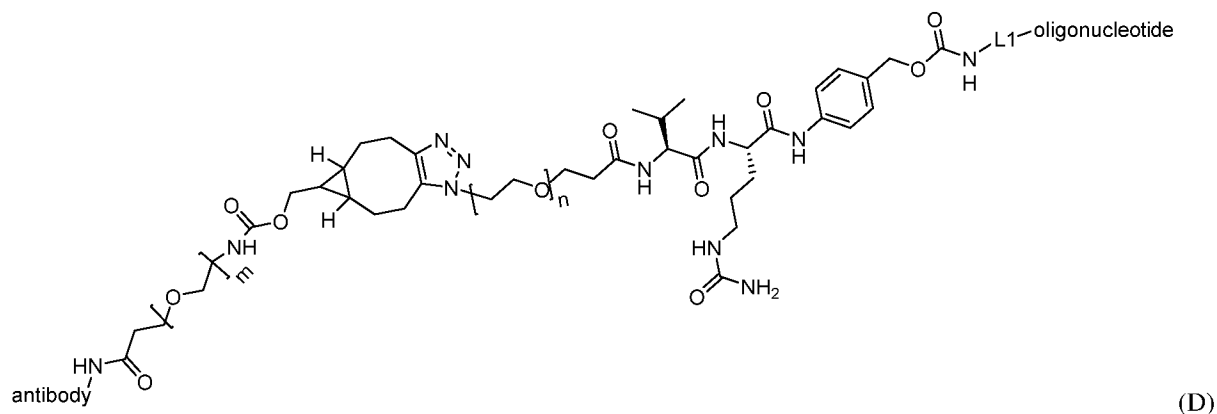
[000321] Further provided herein are non-limiting examples of complexes comprising any one the anti-TfR1 antibodies described herein covalently linked to any of the molecular payloads (e.g., an oligonucleotide) described herein. In some embodiments, the anti-TfR1 antibody (e.g., any one of the anti-TfR1 antibodies provided in **Tables 2-7**) is covalently linked to a molecular payload (e.g., an oligonucleotide such as the oligonucleotides provided in **Table 8**) via a linker. Any of the linkers described herein may be used. In some embodiments, if the molecular payload is an oligonucleotide, the linker is covalently linked to the 5' end, the 3' end, or internally of the oligonucleotide. In some embodiments, the linker is covalently linked to the anti-TfR1 antibody via a thiol-reactive linkage (e.g., via a cysteine in the anti-TfR1 antibody). In some embodiments, the linker is covalently linked to the antibody (e.g., an anti-TfR1 antibody described herein) via a n amine group (e.g., via a lysine in the antibody). In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000322] An example of a structure of a complex comprising an anti-TfR1 antibody covalently linked to a molecular payload via a linker is provided below:

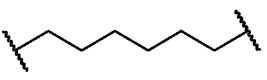


wherein the linker is covalently linked to the antibody via a thiol-reactive linkage (e.g., via a cysteine in the antibody). In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000323] Another example of a structure of a complex comprising an anti-TfR1 antibody covalently linked to a molecular payload via a linker is provided below:



wherein n is a number between 0-10, wherein m is a number between 0-10, wherein the linker is covalently linked to the antibody via an amine group (e.g., on a lysine residue), and/or (e.g., and) wherein the linker is covalently linked to the oligonucleotide (e.g., at the 5' end, 3' end, or internally). In some embodiments, the linker is covalently linked to the antibody via a lysine, the linker is covalently linked to the oligonucleotide at the 5' end, n is 3, and m is 4. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

In some embodiments, $L1$ is .

[000324] It should be appreciated that antibodies can be covalently linked to molecular payloads with different stoichiometries, a property that may be referred to as a drug to antibody ratios (DAR) with the “drug” being the molecular payload. In some embodiments, one molecular payload is covalently linked to an antibody (DAR = 1). In some embodiments, two molecular payloads are covalently linked to an antibody (DAR = 2). In some embodiments, three molecular payloads are covalently linked to an antibody (DAR = 3). In some embodiments, four molecular payloads are covalently linked to an antibody (DAR = 4). In some

embodiments, a mixture of different complexes, each having a different DAR, is provided. In some embodiments, an average DAR of complexes in such a mixture may be in a range of 1 to 3, 1 to 4, 1 to 5 or more. DAR may be increased by conjugating molecular payloads to different sites on an antibody and/or (e.g., and) by conjugating multimers to one or more sites on antibody. For example, a DAR of 2 may be achieved by conjugating a single molecular payload to two different sites on an antibody or by conjugating a dimer molecular payload to a single site of an antibody.

[000325] In some embodiments, the complex described herein comprises an anti-TfR1 antibody described herein (e.g., the antibodies provided in **Tables 2-7**) covalently linked to a molecular payload. In some embodiments, the complex described herein comprises an anti-TfR1 antibody described herein (e.g., the antibodies provided in **Tables 2-7**) covalently linked to molecular payload via a linker. In some embodiments, the linker is covalently linked to the antibody (e.g., an anti-TfR1 antibody described herein) via a thiol-reactive linkage (e.g., via a cysteine in the antibody). In some embodiments, the linker is covalently linked to the antibody (e.g., an anti-TfR1 antibody described herein) via an amine group (e.g., via a lysine in the antibody). In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000326] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a CDR-H1, a CDR-H2, a CDR-H3, a CDR-L1, a CDR-L2, and a CDR-L3 of any one of the antibodies listed in **Table 2**. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000327] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a VH comprising the amino acid sequence of SEQ ID NO: 69, SEQ ID NO: 71, or SEQ ID NO: 72, and a VL comprising the amino acid sequence of SEQ ID NO: 70. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000328] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a VH comprising the amino acid sequence of SEQ ID NO: 73 or SEQ ID NO: 76, and a VL comprising the amino acid sequence of SEQ ID NO: 74. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000329] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a VH comprising the amino acid sequence of SEQ ID NO: 73 or SEQ ID NO: 76, and a VL comprising the amino acid sequence of SEQ ID NO: 75. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000330] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a VH comprising the amino acid sequence of SEQ ID NO: 77, and a VL comprising the amino acid sequence of SEQ ID NO: 78. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000331] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a VH comprising the amino acid sequence of SEQ ID NO: 77 or SEQ ID NO: 79, and a VL comprising the amino acid sequence of SEQ ID NO: 80. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000332] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a VH comprising the amino acid sequence of SEQ ID NO: 154, and a VL comprising the amino acid sequence of SEQ ID NO: 155. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000333] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 84, SEQ ID NO: 86 or SEQ ID NO: 87 and a light chain comprising the amino acid sequence of SEQ ID NO: 85. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000334] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 88 or SEQ ID NO: 91, and a light chain comprising the amino acid sequence of SEQ ID NO: 89. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000335] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 88 or SEQ ID NO: 91, and a light chain comprising the amino acid sequence of SEQ ID NO: 90. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000336] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 92 or SEQ ID NO: 94, and a light chain comprising the amino acid sequence of SEQ ID NO: 95. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000337] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 92, and a light chain comprising the amino acid sequence of SEQ ID NO: 93. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000338] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 156, and a light chain comprising the amino acid sequence of SEQ ID NO: 157. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000339] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 97, SEQ ID NO: 98, or SEQ ID NO: 99 and a VL comprising the amino acid sequence of SEQ ID NO: 85. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000340] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 100 or SEQ ID NO: 101 and a light chain comprising the amino acid sequence of SEQ ID NO: 89. In some embodiments, the

molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

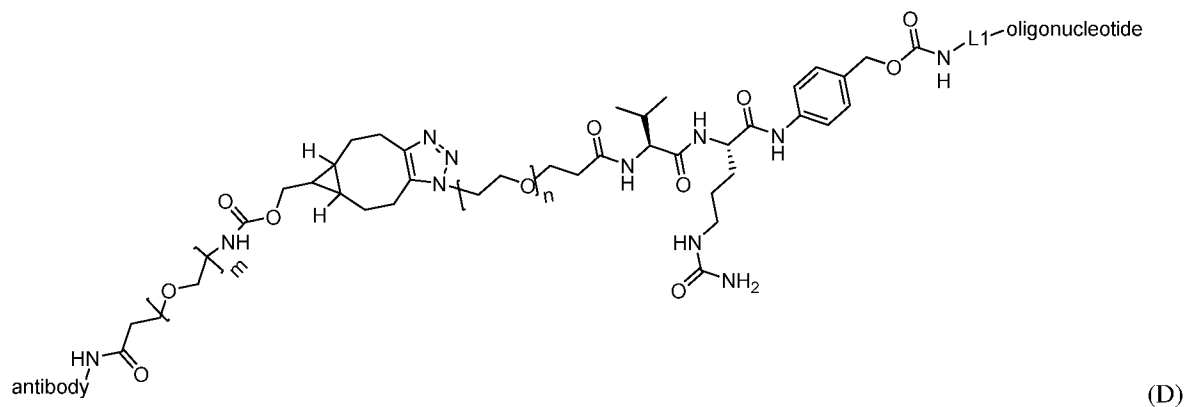
[000341] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 100 or SEQ ID NO: 101 and a light chain comprising the amino acid sequence of SEQ ID NO: 90. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000342] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 102 and a light chain comprising the amino acid sequence of SEQ ID NO: 93. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

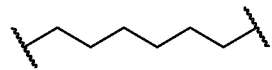
[000343] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 102 or SEQ ID NO: 103 and a light chain comprising the amino acid sequence of SEQ ID NO: 95. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

[000344] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to a molecular payload, wherein the anti-TfR1 antibody comprises a heavy chain comprising the amino acid sequence of SEQ ID NO: 158 or SEQ ID NO: 159 and a light chain comprising the amino acid sequence of SEQ ID NO: 157. In some embodiments, the molecular payload is an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**).

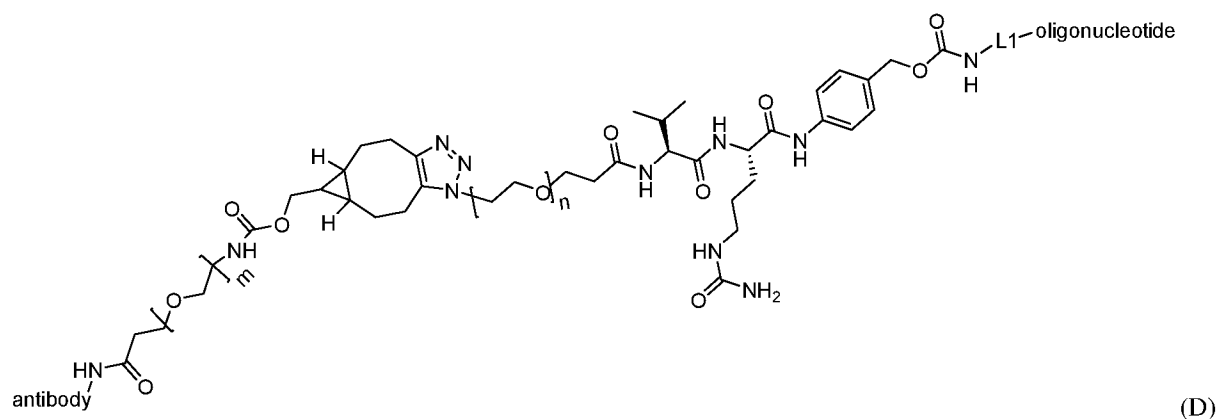
[000345] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to the 5' end of an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**) via a lysine in the anti-TfR1 antibody, wherein the anti-TfR1 antibody comprises a CDR-H1, a CDR-H2, a CDR-H3, a CDR-L1, a CDR-L2, and a CDR-L3 of any one of the antibodies listed in **Table 2**, wherein the complex has a structure of:



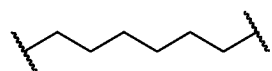
wherein n is 3 and m is 4. In some embodiments, $L1$ is



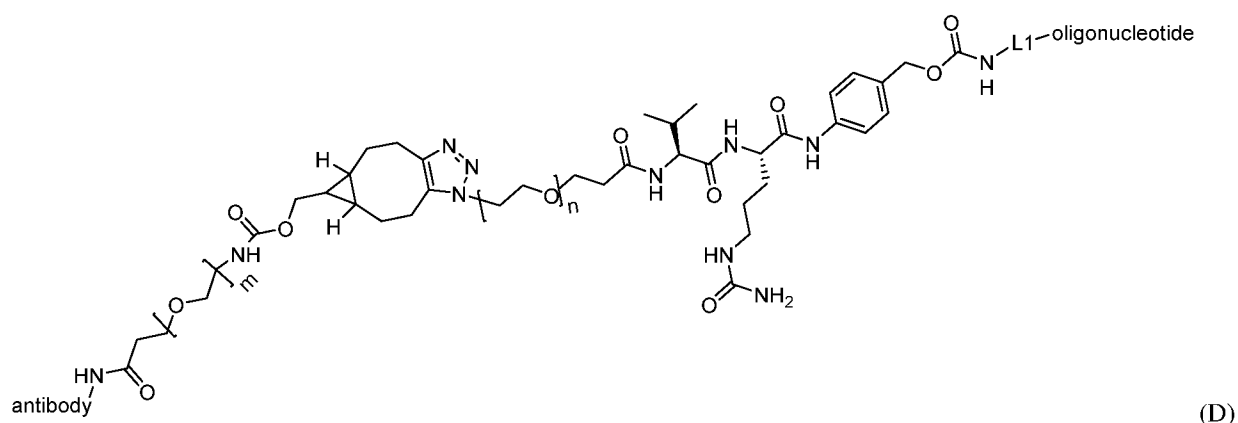
[000346] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to the 5' end of an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**) via a lysine in the anti-TfR1 antibody, wherein the anti-TfR1 antibody comprises a VH and VL of any one of the antibodies listed in **Table 3**, wherein the complex has a structure of:



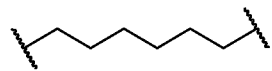
wherein n is 3 and m is 4. In some embodiments, $L1$ is



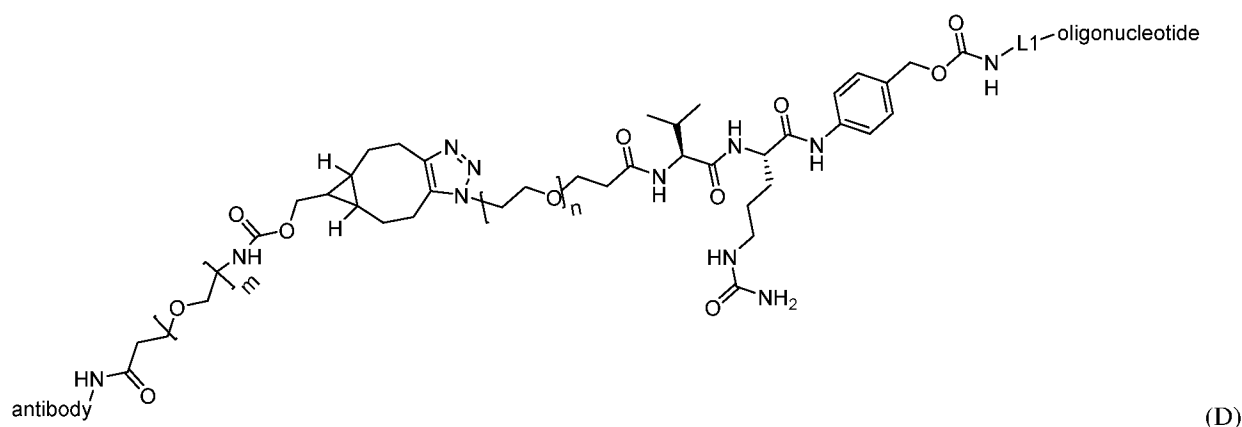
[000347] In some embodiments, the complex described herein comprises an anti-TfR1 antibody covalently linked to the 5' end of an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**) via a lysine in the anti-TfR1 antibody, wherein the anti-TfR1 antibody comprises a heavy chain and light chain of any one of the antibodies listed in **Table 4**, wherein the complex has a structure of:



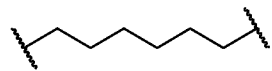
wherein n is 3 and m is 4. In some embodiments, L1 is



[000348] In some embodiments, the complex described herein comprises an anti-TfR1 Fab covalently linked to the 5' end of an FXN-targeting oligonucleotide (e.g., an FXN-targeting oligonucleotide listed in **Table 8**) via a lysine in the anti-TfR1 antibody, wherein the anti-TfR1 Fab comprises a heavy chain and light chain of any one of the antibodies listed in **Table 5**, wherein the complex has a structure of:



wherein n is 3 and m is 4. In some embodiments, L1 is



[000349] In some embodiments, L1 is linked to a 5' phosphate of the oligonucleotide. In some embodiments, L1 is linked to a 5' phosphorothioate of the oligonucleotide. In some embodiments, L1 is linked to a 5' phosphonoamidate of the oligonucleotide.

[000350] In some embodiments, L1 is linked to a 5' phosphate of the oligonucleotide. In some embodiments, the linkage of L1 to a 5' phosphate of the oligonucleotide forms a phosphodiester bond between L1 and the oligonucleotide.

[000351] In some embodiments, L1 is linked to a 3' phosphate of the oligonucleotide. In some embodiments, the linkage of L1 to a 3' phosphate of the oligonucleotide forms a phosphodiester bond between L1 and the oligonucleotide.

[000352] In some embodiments, L1 is optional (e.g., need not be present).

III. Formulations

[000353] Complexes provided herein may be formulated in any suitable manner.

Generally, complexes provided herein are formulated in a manner suitable for pharmaceutical use. For example, complexes can be delivered to a subject using a formulation that minimizes degradation, facilitates delivery and/or (e.g., and) uptake, or provides another beneficial property to the complexes in the formulation. In some embodiments, provided herein are compositions comprising complexes and pharmaceutically acceptable carriers. Such compositions can be suitably formulated such that when administered to a subject, either into the immediate environment of a target cell or systemically, a sufficient amount of the complexes enter target muscle cells. In some embodiments, complexes are formulated in buffer solutions such as phosphate-buffered saline solutions, liposomes, micellar structures, and capsids.

[000354] It should be appreciated that, in some embodiments, compositions may include separately one or more components of complexes provided herein (e.g., muscle-targeting agents, linkers, molecular payloads, or precursor molecules of any one of them).

[000355] In some embodiments, complexes are formulated in water or in an aqueous solution (e.g., water with pH adjustments). In some embodiments, complexes are formulated in basic buffered aqueous solutions (e.g., PBS). In some embodiments, formulations as disclosed herein comprise an excipient. In some embodiments, an excipient confers to a composition improved stability, improved absorption, improved solubility and/or (e.g., and) therapeutic enhancement of the active ingredient. In some embodiments, an excipient is a buffering agent (e.g., sodium citrate, sodium phosphate, a tris base, or sodium hydroxide) or a vehicle (e.g., a buffered solution, petrolatum, dimethyl sulfoxide, or mineral oil).

[000356] In some embodiments, a complex or component thereof (e.g., oligonucleotide or antibody) is lyophilized for extending its shelf-life and then made into a solution before use (e.g., administration to a subject). Accordingly, an excipient in a composition comprising a complex, or component thereof, described herein may be a lyoprotectant (e.g., mannitol, lactose, polyethylene glycol, or polyvinyl pyrrolidone), or a collapse temperature modifier (e.g., dextran, ficoll, or gelatin).

[000357] In some embodiments, a pharmaceutical composition is formulated to be compatible with its intended route of administration. Examples of routes of administration include parenteral, e.g., intravenous, intradermal, subcutaneous, administration. Typically, the route of administration is intravenous or subcutaneous.

[000358] Pharmaceutical compositions suitable for injectable use include sterile aqueous solutions (where water soluble) or dispersions and sterile powders for the extemporaneous preparation of sterile injectable solutions or dispersions. The carrier can be a solvent or dispersion medium containing, for example, water, ethanol, polyol (for example, glycerol, propylene glycol, and liquid polyethylene glycol, and the like), and suitable mixtures thereof. In some embodiments, formulations include isotonic agents, for example, sugars, polyalcohols such as mannitol, sorbitol, and sodium chloride in the composition. Sterile injectable solutions can be prepared by incorporating the complexes in a required amount in a selected solvent with one or a combination of ingredients enumerated above, as required, followed by filtered sterilization.

[000359] In some embodiments, a composition may contain at least about 0.1% of the complex, or component thereof, or more, although the percentage of the active ingredient(s) may be between about 1% and about 80% or more of the weight or volume of the total composition. Factors such as solubility, bioavailability, biological half-life, route of administration, product shelf life, as well as other pharmacological considerations will be contemplated by one skilled in the art of preparing such pharmaceutical formulations, and as such, a variety of dosages and treatment regimens may be desirable.

IV. Methods of Use / Treatment

[000360] Complexes comprising a muscle-targeting agent covalently linked to a molecular payload as described herein are effective in treating Friedreich's Ataxia (FA). In some embodiments, FA is associated with an expansion of a GAA trinucleotide repeat in intron 1 of both FXN alleles. In some embodiments, the nucleotide expansions lead to epigenetic changes and formation of heterochromatin near the repeats, leading to reduced expression of FXN.

[000361] In some embodiments, a subject may be a human subject, a non-human primate subject, a rodent subject, or any suitable mammalian subject. In some embodiments, a subject may have Friedreich's Ataxia. In some embodiments, a subject has a FXN allele, which may optionally contain a disease-associated repeat. In some embodiments, a subject may have a FXN allele with an expanded disease-associated-repeat that comprises about 2-10 repeat units, about 2-50 repeat units, about 2-100 repeat units, about 50-1,000 repeat units, about 50-500 repeat units, about 50-250 repeat units, about 50-100 repeat units, about 500-10,000 repeat units, about 500-5,000 repeat units, about 500-2,500 repeat units, about 500-1,000 repeat units, or about 1,000-10,000 repeat units. In some embodiments, a subject is suffering from symptoms of FA, e.g., hypertrophic cardiomyopathy, muscle atrophy, or muscle weakness. In some

embodiments, a subject is not suffering from symptoms of FA. In some embodiments, subjects have congenital hypertrophic cardio myopathy.

[000362] An aspect of the disclosure includes a method involving administering to a subject an effective amount of a complex as described herein. In some embodiments, an effective amount of a pharmaceutical composition that comprises a complex comprising a muscle-targeting agent covalently linked to a molecular payload can be administered to a subject in need of treatment. In some embodiments, a pharmaceutical composition comprising a complex as described herein may be administered by a suitable route, which may include intravenous administration, e.g., as a bolus or by continuous infusion over a period of time. In some embodiments, intravenous administration may be performed by intramuscular, intraperitoneal, intracerebrospinal, subcutaneous, intra-articular, intrasynovial, or intrathecal routes. In some embodiments, a pharmaceutical composition may be in solid form, aqueous form, or a liquid form. In some embodiments, an aqueous or liquid form may be nebulized or lyophilized. In some embodiments, a nebulized or lyophilized form may be reconstituted with an aqueous or liquid solution.

[000363] Compositions for intravenous administration may contain various carriers such as vegetable oils, dimethylactamide, dimethylformamide, ethyl lactate, ethyl carbonate, isopropyl myristate, ethanol, and polyols (glycerol, propylene glycol, liquid polyethylene glycol, and the like). For intravenous injection, water soluble antibodies can be administered by the drip method, whereby a pharmaceutical formulation containing the antibody and a physiologically acceptable excipients is infused. Physiologically acceptable excipients may include, for example, 5% dextrose, 0.9% saline, Ringer's solution or other suitable excipients. Intramuscular preparations, e.g., a sterile formulation of a suitable soluble salt form of the antibody, can be dissolved and administered in a pharmaceutical excipient such as Water-for-Injection, 0.9% saline, or 5% glucose solution.

[000364] In some embodiments, a pharmaceutical composition that comprises a complex comprising a muscle-targeting agent covalently linked to a molecular payload is administered via site-specific or local delivery techniques. Examples of these techniques include implantable depot sources of the complex, local delivery catheters, site specific carriers, direct injection, or direct application.

[000365] In some embodiments, a pharmaceutical composition that comprises a complex comprising a muscle-targeting agent covalently linked to a molecular payload is administered at an effective concentration that confers therapeutic effect on a subject. Effective amounts vary, as recognized by those skilled in the art, depending on the severity of the disease, unique characteristics of the subject being treated, e.g., age, physical conditions, health, or weight, the

duration of the treatment, the nature of any concurrent therapies, the route of administration and related factors. These related factors are known to those in the art and may be addressed with no more than routine experimentation. In some embodiments, an effective concentration is the maximum dose that is considered to be safe for the patient. In some embodiments, an effective concentration will be the lowest possible concentration that provides maximum efficacy.

[000366] Empirical considerations, e.g., the half-life of the complex in a subject, generally will contribute to determination of the concentration of pharmaceutical composition that is used for treatment. The frequency of administration may be empirically determined and adjusted to maximize the efficacy of the treatment.

[000367] The efficacy of treatment may be assessed using any suitable methods. In some embodiments, the efficacy of treatment may be assessed by evaluation of observation of symptoms associated with FA, e.g., hypertrophic cardiomyopathy, muscle atrophy, or muscle weakness, through measures of a subject's self-reported outcomes, e.g., mobility, self-care, usual activities, pain/discomfort, and anxiety/depression, or by quality-of-life indicators, e.g., lifespan.

[000368] In some embodiments, a pharmaceutical composition that comprises a complex comprising a muscle-targeting agent covalently linked to a molecular payload described herein is administered to a subject at an effective concentration sufficient to inhibit activity or expression of a target gene by at least 10%, at least 20%, at least 30%, at least 40%, at least 50%, at least 60%, at least 70%, at least 80%, at least 90% or at least 95% relative to a control, e.g. baseline level of gene expression prior to treatment.

[000369] In some embodiments, a single dose or administration of a pharmaceutical composition that comprises a complex comprising a muscle-targeting agent covalently linked to a molecular payload described herein to a subject is sufficient to inhibit activity or expression of a target gene for at least 1-5, 1-10, 5-15, 10-20, 15-30, 20-40, 25-50, or more days. In some embodiments, a single dose or administration of a pharmaceutical composition that comprises a complex comprising a muscle-targeting agent covalently linked to a molecular payload described herein to a subject is sufficient to inhibit activity or expression of a target gene for at least 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 15, 20, or 24 weeks. In some embodiments, a single dose or administration of a pharmaceutical composition that comprises a complex comprising a muscle-targeting agent covalently linked to a molecular payload described herein to a subject is sufficient to inhibit activity or expression of a target gene for at least 1-5, 1-10, 2-5, 2-10, 4-8, 4-12, 5-10, 5-12, 5-15, 8-12, 8-15, 10-12, 10-15, 10-20, 12-15, 12-20, 15-20, or 15-25 weeks. In some embodiments, a single dose or administration of a pharmaceutical composition that comprises a complex comprising a muscle-targeting agent covalently linked to a molecular

payload described herein to a subject is sufficient to inhibit activity or expression of a target gene for at least 1, 2, 3, 4, 5, or 6 months.

[000370] In some embodiments, a pharmaceutical composition may comprise more than one complex comprising a muscle-targeting agent covalently linked to a molecular payload. In some embodiments, a pharmaceutical composition may further comprise any other suitable therapeutic agent for treatment of a subject, e.g., a human subject having FA. In some embodiments, the other therapeutic agents may enhance or supplement the effectiveness of the complexes described herein. In some embodiments, the other therapeutic agents may function to treat a different symptom or disease than the complexes described herein.

EXAMPLES

Example 1. *In vitro* activity of FXN-targeting oligonucleotides (ASOs)

[000371] An *in vitro* experiment was conducted to determine the activity of FXN-targeting oligonucleotides (ASOs) listed in **Table 8**. The oligonucleotides target the region of FXN RNA that contains the GAA repeats (the repeat region). The ability of the oligonucleotides in knocking down FXN RNA level is an indication of the accessibility of the target sequences in the repeat region. Accessible target sequences can be targeted by oligonucleotides for inhibiting R-loop formation between the FXN RNA containing expanded repeats and chromosomal DNA to thereby enhance FXN protein expression.

[000372] To replicate the gene expression profile of Friedreich's Ataxia, endogenous FXN mRNA was knocked down in LS 174T colorectal adenocarcinoma cells. Following knockdown, LS 174T cells were seeded at a density of 15,000 cells per well in a 96-well plate and incubated overnight. Following overnight incubation, the cells were transfected with FXN-targeting oligonucleotides at either 20nM or 5nM using Lipofectamine RNAiMax in technical quadruplicate. Cells were subsequently incubated for 72 hours then harvested. Transcript levels were evaluated using a branched DNA assay specific to FXN. All transcript data were normalized to a reference branched DNA assay that measures GAPDH transcript levels. Quadruplicate values were averaged to report a mean transcript level. **Table 9** shows mean remaining transcript levels (%) after treating with each ASO, with transcript levels reported as FXN transcript levels normalized to GAPDH transcript levels and averaged across four replicates. The standard deviation for each set of quadruplicates is also reported.

Table 9. Increasing expression of FXN in LS 174T cells

ASO ID	Mean Remaining Transcript Level at 20nM (%) ($\pm$ Standard Deviation)	Mean Remaining Transcript Level at 5nM (%) ($\pm$ Standard Deviation)
1	72.0 $\pm$ 3.7	74.3 $\pm$ 6.4
2	64.4 $\pm$ 14.6	85.0 $\pm$ 15.8
3	60.5 $\pm$ 8.6	82.3 $\pm$ 6.2
4	78.2 $\pm$ 7.6	97.1 $\pm$ 13.8
5	84.3 $\pm$ 22.7	99.0 $\pm$ 13.7
6	95.8 $\pm$ 11.6	99.8 $\pm$ 7.1
7	36.7 $\pm$ 5.3	52.5 $\pm$ 2.3
8	38.0 $\pm$ 3.6	51.6 $\pm$ 3.6
9	31.4 $\pm$ 8.8	47.8 $\pm$ 6.7
10	36.4 $\pm$ 3.6	61.1 $\pm$ 6.2
11	58.4 $\pm$ 5.0	70.7 $\pm$ 6.5
12	56.0 $\pm$ 8.3	82.0 $\pm$ 10.1
13	91.2 $\pm$ 5.0	120.7 $\pm$ 10.0
14	91.7 $\pm$ 13.1	116.6 $\pm$ 10.4
15	79.5 $\pm$ 6.0	120.1 $\pm$ 10.8
16	87.8 $\pm$ 4.9	119.1 $\pm$ 14.7
17	83.9 $\pm$ 7.4	119.6 $\pm$ 12.2
18	83.9 $\pm$ 17.9	122.0 $\pm$ 9.3

* The ASO numbers correspond to the ASO numbers in Table 8. All ASOs are the modified version as indicated in Table 8.

Example 2: FXN-Targeting ASOs – Dose Response

[000373] Five ASOs targeting FXN mRNA (Table 10) were tested for their ability to knockdown FXN mRNA in a dose-response experiment in LS 174T colorectal adenocarcinoma cells. The LS 174T cells were seeded at a density of 15,000 cells per well in a 96 well plate and allowed to recover overnight. The next day, cells were transfected with FXN-targeting ASOs at various concentrations using Lipofectamine RNAiMax in technical quadruplicate. Cells were incubated for 72 hours and harvested. Dose response analysis including calculation of IC₂₀ and IC₅₀ values for the tested ASOs was performed and results are shown in Table 10.

Table 10. Luciferase reporter assay using FXN-targeting oligonucleotides (ASO)

ASO ID	IC ₂₀ [pM]	IC ₅₀ [pM]	Maximum Inhibition [%]
7	0.026	0.82	70.50
8	0.044	0.55	75.40
9	0.006	1.74	68.30
10	0.036	9.68	62.90
11	0.818	6.24	63.70

* The ASO numbers correspond to the ASO numbers in Table 8. All ASOs are the modified version as indicated in Table 8.

Example 3. In vivo activity of conjugates containing anti-TfR1 Fab conjugated to DMPK-targeting oligonucleotide in mice expressing human TfR1

[000374] Conjugates containing anti-TfR1 Fab 3M12-VH4/VK3 conjugated to a DMPK-targeting oligonucleotide were tested in a mouse model that expresses human TfR1. The anti-TfR Fab1 3M12-VH4/VK3 was conjugated to a DMPK-targeting oligonucleotide via a cleavable linker having the structure of Formula (I). The conjugate was administered to the mice at a dose equivalent to 10 mg/kg oligonucleotide on day 0 and day 7. Mice were sacrificed on day 14 and different muscle tissues were collected and analyzed for *dmpk* mRNA level and oligonucleotide concentration in the tissue. The conjugate reduced mouse wild-type *dmpk* in Tibialis Anterior by 79% (FIG. 1A), in gastrocnemius by 76% (FIG. 1B), in the heart by 70% (FIG. 1C), and in diaphragm by 88% (FIG. 1D). Oligonucleotide distributions in Tibialis Anterior, gastrocnemius, heart, and diaphragm are shown in FIGs. 1E-1H.

[000375] These data indicate that anti-TfR Fab1 3M12-VH4/VK3 enabled cellular internalization of the conjugate into muscle-specific tissues in an *in vivo* mouse model, thereby allowing the DMPK-targeting oligonucleotide to reduce expression of DMPK. Similarly, an anti-TfR1 antibody (e.g., anti-TfR1 Fab 3M12-VH4/VK3) can enable cellular internalization of a conjugate containing the anti-TfR1 antibody conjugated to an FXN-targeting oligonucleotide for enhancing FXN protein expression.

EQUIVALENTS AND TERMINOLOGY

[000376] The disclosure illustratively described herein suitably can be practiced in the absence of any element or elements, limitation or limitations that are not specifically disclosed herein. Thus, for example, in each instance herein any of the terms “comprising”, “consisting essentially of”, and “consisting of” may be replaced with either of the other two terms. The terms and expressions which have been employed are used as terms of description and not of limitation, and there is no intention that in the use of such terms and expressions of excluding any equivalents of the features shown and described or portions thereof, but it is recognized that various modifications are possible within the scope of the disclosure. Thus, it should be understood that although the present disclosure has been specifically disclosed by preferred embodiments, optional features, modification and variation of the concepts herein disclosed may be resorted to by those skilled in the art, and that such modifications and variations are considered to be within the scope of this disclosure.

[000377] In addition, where features or aspects of the disclosure are described in terms of Markush groups or other grouping of alternatives, those skilled in the art will recognize that the

disclosure is also thereby described in terms of any individual member or subgroup of members of the Markush group or other group.

[000378] It should be appreciated that, in some embodiments, sequences presented in the sequence listing may be referred to in describing the structure of an oligonucleotide or other nucleic acid. In such embodiments, the actual oligonucleotide or other nucleic acid may have one or more alternative nucleotides or nucleosides (e.g., an RNA counterpart of a DNA nucleoside or a DNA counterpart of an RNA nucleoside) and/or (e.g., and) one or more modified nucleotides/nucleosides and/or (e.g., and) one or more modified internucleoside linkages and/or (e.g., and) one or more other modification compared with the specified sequence while retaining essentially same or similar complementary properties as the specified sequence.

[000379] The use of the terms “a” and “an” and “the” and similar referents in the context of describing the invention (especially in the context of the following claims) are to be construed to cover both the singular and the plural, unless otherwise indicated herein or clearly contradicted by context. The terms “comprising,” “having,” “including,” and “containing” are to be construed as open-ended terms (*i.e.*, meaning “including, but not limited to,”) unless otherwise noted. Recitation of ranges of values herein are merely intended to serve as a shorthand method of referring individually to each separate value falling within the range, unless otherwise indicated herein, and each separate value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of any and all examples, or exemplary language (*e.g.*, “such as”) provided herein, is intended merely to better illuminate the invention and does not pose a limitation on the scope of the invention unless otherwise claimed. No language in the specification should be construed as indicating any non-claimed element as essential to the practice of the invention.

[000380] Embodiments of this invention are described herein. Variations of those embodiments may become apparent to those of ordinary skill in the art upon reading the foregoing description.

[000381] The inventors expect skilled artisans to employ such variations as appropriate, and the inventors intend for the invention to be practiced otherwise than as specifically described herein. Accordingly, this invention includes all modifications and equivalents of the subject matter recited in the claims appended hereto as permitted by applicable law. Moreover, any combination of the above-described elements in all possible variations thereof is encompassed by the invention unless otherwise indicated herein or otherwise clearly contradicted by context. Those skilled in the art will recognize, or be able to ascertain using no more than routine experimentation, many equivalents to the specific embodiments of the invention described herein. Such equivalents are intended to be encompassed by the following claims.

CLAIMS

What is claimed is:

1. A complex comprising a muscle-targeting agent covalently linked to an oligonucleotide configured for increasing FXN expression, wherein the oligonucleotide comprises a region of complementarity to a repeat region of an FXN RNA, wherein the repeat region comprises a target sequence as set forth in any one of SEQ ID NOs: 162-164, and wherein the region of complementarity is at least 12 nucleotides in length.
2. The complex of claim 1, wherein the muscle-targeting agent is an anti-transferrin receptor 1 (TfR1) antibody.
3. The complex of claim 1 or claim 2, wherein the oligonucleotide comprises at least 16 consecutive nucleotides of any one of SEQ ID NOs: 165-176, wherein each of the Us are optionally and independently Ts, optionally wherein the oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 165-176, and wherein each of the Us are optionally and independently Ts.
4. The complex of any one of claims 1-3, wherein the oligonucleotide comprises a 5'-X-Y-Z-3' configuration, wherein
 - X comprises 3-5 linked nucleosides, wherein at least one of the nucleosides in X is a 2'-modified nucleoside;
 - Y comprises 6-14 linked 2'-deoxyribonucleosides, wherein each cytidine in Y is optionally and independently a 5-methyl-cytidine; and
 - Z comprises 3-5 linked nucleosides, wherein at least one of the nucleosides in Z is a 2'-modified nucleoside.
5. The complex of claim 4, wherein the oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 165-167, wherein X comprises 5 linked nucleosides and each nucleoside in X is a 2'-MOE modified nucleoside; Y comprises 10 linked 2'-deoxyribonucleosides, wherein each cytidine in Y is optionally and independently a 5-methyl-cytidine; and Z comprises 5 linked nucleosides and each nucleoside in Z is a 2'-MOE modified nucleoside.
6. The complex of claim 4, wherein the oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 165-167, wherein X comprises 5 linked nucleosides, wherein each nucleoside in X is a LNA nucleoside; Y comprises 10 linked 2'-deoxyribonucleosides, wherein

each cytidine in Y is optionally and independently a 5-methyl-cytidine; and Z comprises 5 linked nucleosides, wherein each nucleoside in Z is a LNA nucleoside.

7. The complex of claim 4, wherein the oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 171-173, wherein X comprises 3 linked nucleosides, wherein each nucleoside in X is a LNA nucleoside; Y comprises 14 linked 2'-deoxyribonucleosides, wherein each cytidine in Y is optionally and independently a 5-methyl-cytidine; and Z comprises 3 linked nucleosides, wherein each nucleoside in Z is a LNA nucleoside.

8. The complex of any one of claims 1-3, wherein the oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 168-170, and wherein each nucleoside of the oligonucleotide is a 2'-MOE modified nucleoside.

9. The complex of any one of claims 1-3, wherein the oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 168-170, and wherein each T in the oligonucleotide is a LNA nucleoside, and each C in the oligonucleotide is a 5-methyl-deoxycytidine.

10. The complex of any one of claims 1-3, wherein the oligonucleotide comprises the nucleotide sequence of any one of SEQ ID NOs: 174-176, and wherein each C in the oligonucleotide is a LNA nucleoside and each T is a deoxythymidine.

11. The complex of any one of claims 1-9, wherein the oligonucleotide comprises one or more phosphorothioate internucleoside linkages, optionally wherein the each internucleoside linkage in the oligonucleotide is a phosphorothioate internucleoside linkage.

12. The complex of any one of claims 1-4, wherein the oligonucleotide is selected from:

oC*oU*oU*oC*oU*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*oC*oU*oU*oC*oU (SEQ ID NO: 165)

oU*oU*oC*oU*oU*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*oU*oU*oC*oU*oU (SEQ ID NO: 166)

oU*oC*oU*oU*oC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*oU*oC*oU*oU*oC (SEQ ID NO: 167)

oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU (SEQ ID NO: 168)

oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU (SEQ ID NO: 169)

oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oC (SEQ ID NO: 170)

+C*+U*+U*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*+U*+C*+U (SEQ ID NO: 171)

+U*+U*+C*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*+C*+U*+U (SEQ ID NO: 172)

+U*+C*+U*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*+U*+U*+C (SEQ ID NO: 173)

+C*+U*+U*+C*+U*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*+C*+U*+U*+C*+U (SEQ ID NO: 165)

+U*+U*+C*+U*+U*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*+U*+U*+C*+U*+U (SEQ ID NO: 166)

+U*+C*+U*+U*+C*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*+U*+C*+U*+U*+C (SEQ ID NO: 167)

xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U (SEQ ID NO: 168)

+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U (SEQ ID NO: 169)

+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC (SEQ ID NO: 170)

+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT (SEQ ID NO: 174)

dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT (SEQ ID NO: 175)

dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C (SEQ ID NO: 176)

wherein “xdC” indicates a 5-methyl-deoxycytidine; “dN” indicates a 2’-deoxyribonucleoside; “+N” indicates a LNA nucleoside; “oN” indicates a 2’- MOE modified ribonucleoside; “oC” indicates a 5-methyl-2’-MOE-cytidine; “+C” indicates a 5-methyl-2’-4’-bicyclic-cytidine (2’-4’ methylene bridge); “oU” indicates a 5-methyl-2’-MOE-uridine; “+U” indicates a 5-methyl-2’-4’-bicyclic-uridine (2’-4’ methylene bridge); “*” indicates a phosphorothioate internucleoside linkage.

13. The complex of any one of claims 2-12, wherein the anti-TfR1 antibody comprises a heavy chain complementarity determining region 1 (CDR-H1), a heavy chain complementarity determining region 2 (CDR-H2), a heavy chain complementarity determining region 3 (CDR-H3), a light chain complementarity determining region 1 (CDR-L1), a light chain complementarity determining region 2 (CDR-L2), a light chain complementarity determining region 3 (CDR-L3) of any of the anti-TfR1 antibodies listed in Table 2.

14. The complex of any one of claims 2-13, wherein the anti-TfR1 antibody comprises a heavy chain variable region (VH) and a light chain variable region (VL) of any of the anti-TfR1 antibodies listed in Table 3.

15. The complex of any one of claims 2-13, wherein the anti-TfR1 antibody is a Fab, optionally wherein the Fab comprises a heavy chain and a light chain of any of the anti-TfR1 Fabs listed in Table 5.

16. The complex of any one of claims 1-15, wherein the muscle targeting agent and the oligonucleotide are covalently linked via a linker, optionally wherein the linker comprises a valine-citrulline sequence.

17. The complex of any one of claims 1-16, wherein the FXN RNA contains disease-associated expanded GAA repeats.

18. A method of increasing FXN expression in a muscle cell, the method comprising contacting the muscle cell with an effective amount of the complex of any one of claims 1-17 for promoting internalization of the oligonucleotide to the muscle cell.

19. A method of treating Friedreich’s Ataxia (FA), the method comprising administering to a subject in need thereof an effective amount of the complex of any one of claims 1-17, wherein the subject has a mutant FXN allele comprising disease-associated GAA repeats.

20. The method of claim 18 or claim 19, wherein the complex results in an increase of FXN protein level.

21. An oligonucleotide selected from:

oC*oU*oU*oC*oU*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*oC*oU*oU*oC*oU (SEQ ID NO: 165)
oU*oU*oC*oU*oU*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*oU*oU*oC*oU*oU (SEQ ID NO: 166)
oU*oC*oU*oU*oC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*oU*oC*oU*oU*oC (SEQ ID NO: 167)
oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU (SEQ ID NO: 168)
oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU (SEQ ID NO: 169)
oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC*oU*oU*oC (SEQ ID NO: 170)
+C*+U*+U*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*+U*+C*+U (SEQ ID NO: 171)
+U*+U*+C*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*+C*+U*+U (SEQ ID NO: 172)
+U*+C*+U*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*+U*+U*+C (SEQ ID NO: 173)
+C*+U*+U*+C*+U*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*+C*+U*+U*+C*+U (SEQ ID NO: 165)
+U*+U*+C*+U*+U*xdC*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*+U*+U*+C*+U*+U (SEQ ID NO: 166)
+U*+C*+U*+U*+C*dT*dT*xdC*dT*dT*xdC*dT*dT*xdC*dT*+U*+C*+U*+U*+C (SEQ ID NO: 167)
xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U (SEQ ID NO: 168)
+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U (SEQ ID NO: 169)
+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC*+U*+U*xdC (SEQ ID NO: 170)
+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT (SEQ ID NO: 174)
dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT (SEQ ID NO: 175)
dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C*dT*dT*+C (SEQ ID NO: 176)

wherein “xdC” indicates a 5-methyl-deoxycytidine; “dN” indicates a 2’-deoxyribonucleoside; “+N” indicates a LNA nucleoside; “oN” indicates a 2’- MOE modified ribonucleoside; “oC” indicates a 5-methyl-2’-MOE-cytidine; “+C” indicates a 5-methyl-2’-4’-bicyclic-cytidine (2’-4’ methylene bridge); “oU” indicates a 5-methyl-2’-MOE-uridine; “+U” indicates a 5-methyl-2’-4’-bicyclic-uridine (2’-4’ methylene bridge); “*” indicates a phosphorothioate internucleoside linkage.

22. A composition comprising the oligonucleotide of claim 21 in sodium salt form.

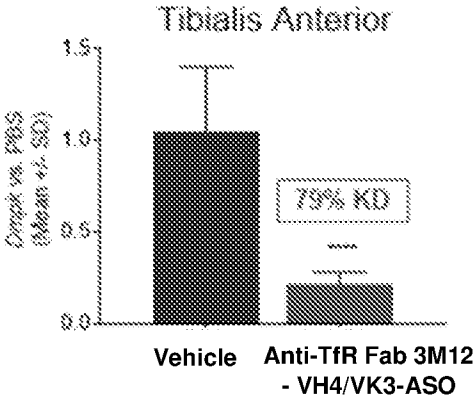


FIG. 1A

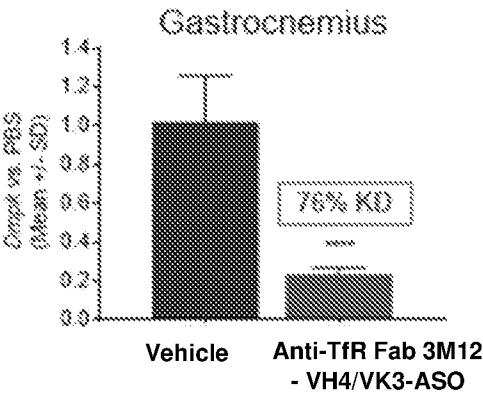


FIG. 1B

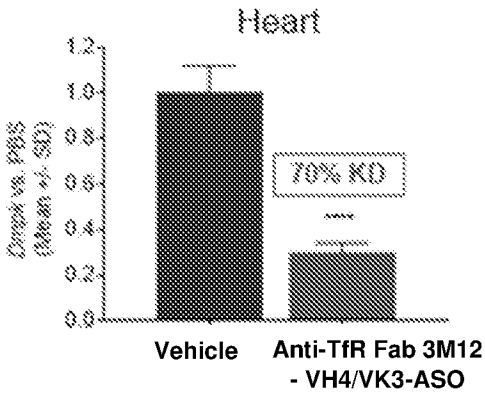


FIG. 1C

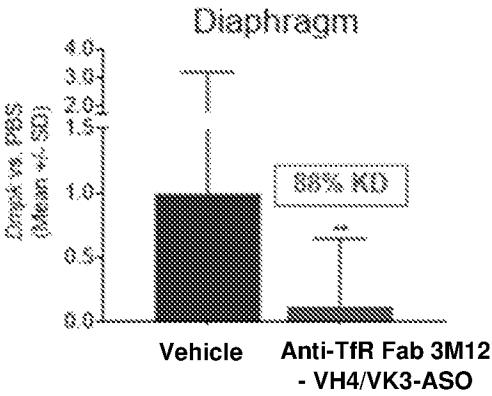


FIG. 1D

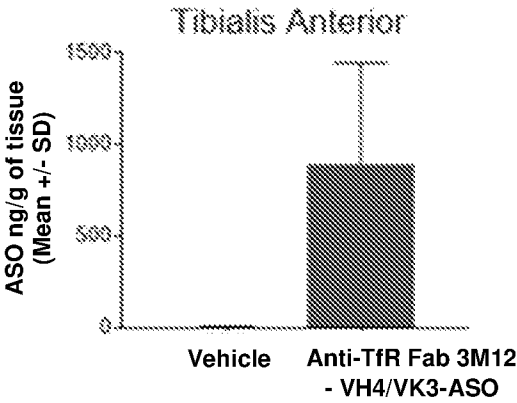


FIG. 1E

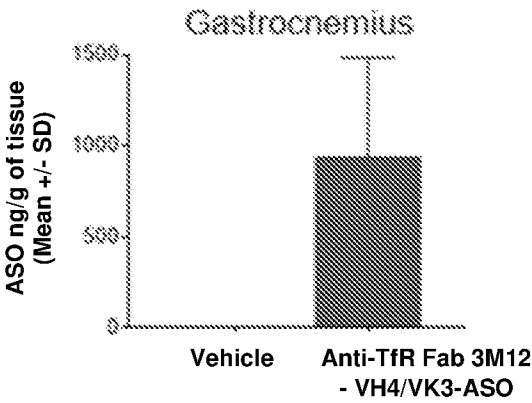


FIG. 1F

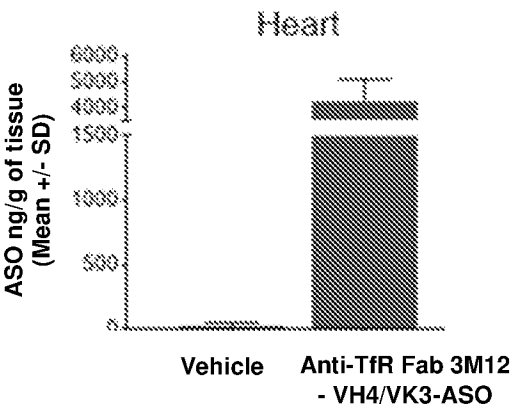


FIG. 1G

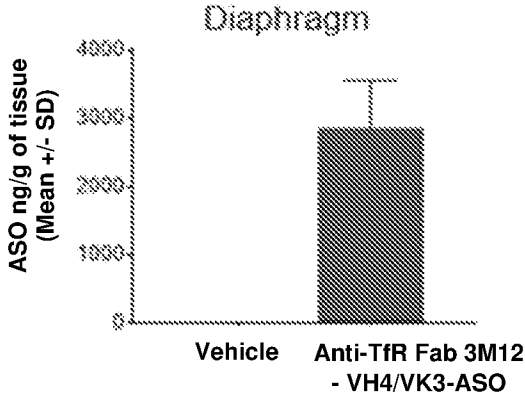


FIG. 1H