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CRISPR/Cas9-mediated gene editing ameliorates neurotoxicity in mouse model of Huntington’s disease

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Huntington’s disease is a neurodegenerative disorder caused by a polyglutamine repeat in the Huntingtin gene (HTT). Although suppressing the expression of mutant HTT (mHTT) has been explored as a therapeutic strategy to treat Huntington’s disease, considerable efforts have gone into developing allele-specific suppression of mHTT expression, given that loss of Htt in mice can lead to embryonic lethality. It remains unknown whether depletion of HTT in the adult brain, regardless of its allele, could be a safe therapy. Here, we report that permanent suppression of endogenous mHTT expression in the striatum of mHTT-expressing mice (HD140Q-knockin mice) using CRISPR/Cas9-mediated inactivation effectively depleted HTT aggregates and attenuated early neuropathology. The reduction of mHTT expression in striatal neuronal cells in adult HD140Q-knockin mice did not affect viability, but alleviated motor deficits. Our studies suggest that non–allele-specific CRISPR/Cas9-mediated gene editing could be used to efficiently and permanently eliminate polyglutamine expansion–mediated neuronal toxicity in the adult brain.

Introduction

Expansion of a CAG/glutamine repeat in various genes causes at least 9 different neurodegenerative diseases, including Huntington’s disease (HD). In HD, the expanded CAG repeat encodes a polyglutamine (polyQ) tract in the N-terminal region of huntingtin (HTT) and leads to a wide range of cellular dysfunctions (1). The gain of toxic function of mutant huntingtin (mHTT) has led to considerable efforts to use siRNA, antisense oligonucleotides, or CRISPR/Cas9 to selectively suppress the expression of mHTT (2–4). Indeed, siRNA and antisense oligonucleotides have shown promising therapeutic effects in HD mice that express transgenic mHTT (2, 5). However, this relies on SNPs that are specific to the mutant allele. Also, whether this strategy can be successfully used in HD mice that express mHTT at the endogenous level remains unknown, since normal and expanded alleles of the endogenous Htt gene are not readily distinguished by siRNA and antisense oligonucleotides (6).

Our recent studies using conditional Htt-KO mice revealed that depletion of normal HTT in adult mouse brains does not affect animal survival, growth, or neuronal viability (7). In addition, knockin (KI) mice that express N-terminal mHTT have shown that the N-terminal region of HTT is not essential for early embryonic development (8). These findings suggest that removal of N-terminal HTT containing the polyQ domain, regardless of its allele, could be a potential therapeutic strategy to treat HD. Here, we report that permanent suppression of the endogenous expression of mHTT via CRISPR/Cas9 in the striatum of HD140Q-KI mice, which express a human HD HTT, can effectively deplete HTT aggregates and early neuropathology, even after the formation of abundant HTT aggregates. Reducing HTT expression in striatal neuronal cells does not affect the viability of the adult HD140Q-KI mice, but alleviates their motor deficits and neurological symptoms. Our findings suggest that depletion of HTT via CRISPR/Cas9 in a non–allele-specific manner can efficiently and permanently eliminate polyQ expansion–mediated neuronal toxicity in the adult brain. This also opens up a new avenue for treating other neurodegenerative diseases caused by the gain-of-function mechanism.

Results and Discussion

To delete the polyQ domain of mHTT using CRISPR/Cas9, we designed 4 guide RNAs (gRNAs) to target the DNA regions (T1, T2, T3, and T4) flanking the CAG repeat in exon 1 of human HTT (Figure 1A and Supplemental Figure 1A; supplemental material available online with this article; https://doi.org/10.1172/JCI92087). We transfected HEK293 cells stably expressing exon 1 of human HTT containing 120 CAG repeats with each of the 4 gRNAs and Cas9. Western blotting showed a reduction of mHTT in the transfected cells (Supplemental Figure 1, B and C). We also tested the activities of combining 2 HTT-gRNAs in the stable HEK293 cells. A combination of T1 and T3 HTT-gRNAs led to the greatest reduction in mHTT (Supplemental Figure 1, D and E) and was used for our subsequent studies.

We next tested the effect of CRISPR/Cas9-mediated HTT depletion in HD140Q-KI mice. In this KI mouse model, exon 1 of human HTT with 140 CAG repeats replaces exon 1 of endog-
Western blotting verified that RFP and Cas9 were predominantly expressed in the injected striatum (Supplemental Figure 2B).

We injected AAV-HTT-gRNA and AAV-CMV-Cas9 into one side of the striatum in homozygous HD140Q-KI mice at the age of 3 or 9 months. The contralateral striatum was injected with AAV-HTT-gRNA or AAV-CMV-Cas9 alone, which allowed us to rigorously examine the efficiency of HTT-gRNA/Cas9–mediated mHTT knockdown. HD140Q-KI mice are known to develop age-dependent motor deficits and nuclear accumulation of mHTT (9, 14). We found that most of the striatum and the needle pathway in the cortex and hippocampus were transduced by AAVs 3 weeks after injection (Figure 1B). Western blotting showed that envous mouse Htt (9), resulting in the expression of full-length mHTT with 140Q under the control of the endogenous mouse Htt promoter. In HD140Q-KI mice, accumulated mHTT in striatal neuronal nuclei is detectable between 4 and 6 months and forms obvious aggregates at 9 to 10 months (8, 10–12). We focused on the striatum to investigate the effect of removing mHTT. Two gRNAs (T1 and T3) are expressed under the U6 promoter in an adeno-associated virus (AAV) vector that also expresses red fluorescent protein (RFP) (AAV-HTT-gRNA), and Cas9 is expressed in another AAV vector under the CMV promoter (AAV-CMV-Cas9) (13). The 2 viruses were mixed at a ratio of 1:4 for stereotaxic injection into mouse striatum (Supplemental Figure 2A). After 3 weeks,
HTT-gRNA, but not control-gRNA, caused a significant reduction of mHTT in the striatum of 9-month-old HD140Q-KI mice (Figure 1C and Supplementary Figure 2C). Compared with the contralateral striatum injected with HTT-gRNA alone, immunostaining revealed a dramatic decrease in the nuclear accumulation and aggregation of mHTT in the HTT-gRNA/Cas9-injected striatum (Figure 1D). Double immunofluorescence staining further verified that the decrease in mHTT staining is dependent on the expression of HTT-gRNA (Figure 1E). In HD KI mouse brain, a well-known early neuropathology is reactive astrocytes (15, 16). In brain regions transduced by HTT-gRNA/Cas9, attenuation of the increased glial fibrillary acidic protein (GFAP) was associated with knockdown of mHTT compared with brain regions injected with control-gRNA/Cas9 (Figure 1C and Supplementary Figure 2C), indicating that a reduction of mHTT alleviated reactive astrocytes. We also checked several other proteins such as NeuN (a neuronal marker), p62 (an autophagy marker) and caspase 3 (an apoptosis marker), which are frequently studied in neurodegenerative diseases, and found that these proteins remained unchanged (Figure 1C and Supplemental Figure 2C). The results were corroborated by immunohistochemical studies using GFAP and NeuN antibodies (Supplemental Figure 3, A and B).

Most HD patients are heterozygous for the HD gene mutation. Also, neurons are preferentially affected in HD. Thus, we tested the therapeutic potential of CRISPR/Cas9 in heterozygous HD140Q-KI mice, using AAV-HTT-gRNA/AAV-MECP2-Cas9 injection. (A) Schematics showing the viral vectors used. HA, human influenza hemagglutinin; ITR, inverted terminal repeat; KASH, Klarsicht, ANC-1, Syne Homology; WPRE, woodchuck hepatitis virus post-transcriptional regulatory element. (B) Double immunostaining with anti–DARRP-32 indicated that medium spiny neurons expressed AAV-HTT-gRNA. Scale bar: 10 μm. (C) Motor functions of heterozygous HD140Q-KI mice injected with AAV-HTT-gRNA/AAV-MECP2-Cas9 (KI HTT-gRNA) or AAV-control-gRNA/AAV-MECP2-Cas9 (KI control-gRNA) and WT mice injected with AAV-control-gRNA/AAV-MECP2-Cas9 (WT) were evaluated using rotarod, balance beam, and grip strength tests at different time points after injection (n = 12 for each group; *P < 0.05, **P < 0.012, and ***P < 0.001, by 2-way ANOVA with Bonferroni’s test, comparing the KI HTT-gRNA group with the KI control-gRNA group). Data represent the mean ± SEM.
KI mice. We were able to obtain 24 nine-month-old heterozygous KI mice for examination, at which age the mice show abundant nuclear accumulation of mHTT in striatal neurons and also develop obvious motor dysfunction. These KI mice were injected with either AAV-HTT-gRNA/AAV-MECP2-Cas9 or AAV-control-gRNA/AAV-MECP2-Cas9, and their behaviors were monitored for 3 months.

In HD140Q-KI mice, motor dysfunction has been well documented using rotarod, balance beam, and grip strength tests (9, 17). We found that HTT-gRNA/Cas9 could significantly improve performance in these tests and alleviate the motor deficits of HD140Q-KI mice. We were able to obtain 24 nine-month-old heterozygous KI mice for examination, at which age the mice show abundant nuclear accumulation of mHTT in striatal neurons and also develop obvious motor dysfunction. These KI mice were injected with either AAV-HTT-gRNA/AAV-MECP2-Cas9 or AAV-control-gRNA/AAV-MECP2-Cas9, and their behaviors were monitored for 3 months.

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show abundant nuclear mHTT accumulation in the striatum and HD-related phenotypes. At the age of 9 months, HD140Q-KI mice also verified that CRISPR/Cas9 could effectively alleviate HD140Q-KI mouse brains to further analyze their pathology and behavior.

Many studies have shown rare off-targets when specific gRNAs are used (18, 19). Whole-genome sequencing analysis using genomic DNA extracted from HTT-gRNA/Cas9–injected striatum verified that genomic mutations predominantly occurred around the HTT-gRNA targeted sequences in the Htt gene, but not in potential off-target loci (Supplemental Figure 5A). We found that the percentage of mHTT reduction in each mouse correlated with its rotarod and balance beam performance (Supplemental Figure 5, B and C).

Increased body weight reductions (Figure 2C), the efficiency of mHTT reduction in the striatum varied among the individual mice tested (Supplemental Figure 5A). We found that the percentage of mHTT reduction in each mouse correlated with its rotarod and balance beam performance (Supplemental Figure 5, B and C).

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mice compared with control-gRNA/Cas9–injected KI and WT mice (Figure 2C). In addition, knocking down HTT expression also attenuated body weight reductions (Figure 2C). The efficiency of mHTT reduction in the striatum varied among the individual mice tested (Supplemental Figure 5A). We found that the percentage of mHTT reduction in each mouse correlated with its rotarod and balance beam performance (Supplemental Figure 5, B and C).

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Although shutting off the expression of transgenic mHTT can alleviate neurological symptoms in HD mice (20, 21), whether reducing the expression of endogenous HTT can be used to treat HD without deleterious effects remains unknown. When we used homozygous HD140Q-KI mice in which 2 alleles of the mHTT gene could be disrupted by CRISPR/Cas9, we found that removal of HTT did not affect the expression of NeuN or caspase 3. Instead, mHTT depletion significantly reduced reactive astrocytes, an early pathological event in HD and in mouse brains (15, 16). The results also support our recent findings that depletion of endogenous mouse HTT in adult neurons is nonlethal and that the function of HTT is cell type and age dependent (7). Using heterozygous HD140Q-KI mice to further analyze their pathology and behaviors, we also verified that CRISPR/Cas9 could effectively alleviate HD-related phenotypes. At the age of 9 months, HD140Q-KI mice show abundant nuclear mHTT accumulation in the striatum and obviou...


