Report

DOK7 gene therapy enhances motor activity and life span in ALS model mice

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Abstract

Amyotrophic lateral sclerosis (ALS) is a progressive, multifactorial motor neurodegenerative disease with severe muscle atrophy. The glutamate release inhibitor riluzole is the only medication approved by the FDA, and prolongs patient life span by a few months, testifying to a strong need for new treatment strategies. In ALS, motor neuron degeneration first becomes evident at the motor nerve terminals in neuromuscular junctions (NMJs), the cholinergic synapse between motor neuron and skeletal muscle; degeneration then progresses proximally, implicating the NMJ as a therapeutic target. We previously demonstrated that activation of muscle-specific kinase MuSK by the cytoplasmic protein Dok-7 is essential for NMJ formation, and forced expression of Dok-7 in muscle activates MuSK and enlarges NMJs. Here, we show that therapeutic administration of an adeno-associated virus vector encoding the human DOK7 gene suppressed motor nerve terminal degeneration at NMJs together with muscle atrophy in the SOD1-G93A ALS mouse model. Ultimately, we show that DOK7 gene therapy enhanced motor activity and life span in ALS model mice.

Keywords amyotrophic lateral sclerosis; DOK7; gene therapy; neuromuscular junction

Subject Categories Genetics, Gene Therapy & Genetic Disease; Neuroscience

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Introduction

Amyotrophic lateral sclerosis (ALS) is a fatal neuromuscular disease with motor neuron degeneration that causes muscle weakness, paralysis, and respiratory failure (Paez-Colasante et al, 2015). It has been established that ALS is a multifactorial disease, and indeed, many abnormalities have been identified as potential pathogenic factors in patients with ALS and its model animals, including accumulation of protein aggregates, defective RNA processing, oxidative stress, glutamate excitotoxicity, glial dysfunction, and abnormal muscle energy metabolism (Paez-Colasante et al, 2015; Zhu et al, 2015). This variation appears to be a roadblock to development of effective therapy (Genç & Özdinler, 2014; Ittner et al, 2015). Currently, the glutamate release inhibitor riluzole is the only medication approved by the FDA for ALS, and prolongs patient life span by a few months (Lucette et al, 1996). Although many other drugs have been under clinical trial, there remains a strong need for new treatment strategies for ALS (Ittner et al, 2015). Recent studies of ALS model mice revealed that motor neuron degeneration first becomes evident as size reduction of the motor nerve terminals and subsequent denervation at neuromuscular junctions (NMJs), a cholinergic synapse essential for motoneural control of muscle contraction (Fischer et al, 2004; Murray et al, 2010; Dadon-Nachum et al, 2011; Valdez et al, 2012). Motor neuron degeneration then progresses proximally. This pattern, known as “dying-back” pathology or distal axonopathy, is also observed in autopsy or electrophysiology of ALS patients (Fischer et al, 2004; Dadon-Nachum et al, 2011; Bruneteau et al, 2015), suggesting that NMJ protection might be an effective treatment.

In mammals, the formation and maintenance of NMJs are orchestrated by the muscle-specific receptor tyrosine kinase MuSK (Burden, 2002), which requires Dok-7 as an essential, muscle-intrinsic activator (Okada et al, 2006; Inoue et al, 2009). Indeed, recessive mutations in the human DOK7 gene cause the congenital myasthenic syndrome DOK7 myasthenia, which is characterized by defective NMJ structure or NMJ synaptopathy (Beeson et al, 2006). Previously, we generated AAV-D7, a recombinant muscle-tropic aden-associated virus (AAV) serotype 9 vector carrying the human DOK7 gene tagged with EGFP under the control of the cytomegalovirus promoter, and demonstrated that therapeutic administration of AAV-D7 enlarges NMJs and enhances motor activity and life span in DOK7 myasthenia model mice (Arimura et al, 2014). Furthermore, therapeutic administration of AAV-D7—DOK7 gene therapy—also enlarged NMJs and enhanced motor activity and life span in a mouse model of autosomal dominant Emery–Dreifuss muscular dystrophy, a disease associated with defective NMJs due to mutations in the lamin A/C gene (Méjat et al, 2009). Although these observations demonstrate potential for DOK7 gene therapy in these myopathies with NMJ defects, we suspected that this therapy might also benefit motor neurodegenerative diseases, because muscle-specific...
overexpression of Dok-7 activates MuSK and enlarges not only the postsynaptic apparatus but also presynaptic motor nerve terminals at NMJs, which might counteract degeneration, or size reduction in particular, of the terminal (Inoue et al, 2009; Arimura et al, 2014). Since degeneration of motor nerve terminals appears to play an important role in pathogenesis of both patients and animal models of ALS (Fischer et al, 2004; Murray et al, 2010; Dadon-Nachum et al, 2011; Valdez et al, 2012; Bruneteau et al, 2015), in the present study we examined whether DOK7 gene therapy ameliorates pathology in a mouse model of ALS.

Results

**DOK7 gene therapy suppresses motor nerve terminal degeneration at the NMJ in ALS mice**

In ~20% of familial cases of ALS, patients harbor a gain-of-function mutation in the gene encoding Cu/Zn superoxide dismutase 1 (SOD1; Ittner et al, 2015; Paez-Colasante et al, 2015). Moreover, C57BL/6 mice expressing human SOD1 (hSOD1) with the ALS-linked G93A mutation (hereafter ALS mice) manifest progressive muscle paralysis similar to that observed in clinical cases along with the histopathological hallmarks observed in familial and sporadic ALS, including NMJ defects (Dadon-Nachum et al, 2011; Zhu et al, 2015). Based on these pathological features, ALS mice have been widely employed as a useful model, although following the guideline for preclinical ALS studies is strongly recommended for achieving results that better translate into humans (see below; Ludolph et al, 2010). Thus, in accord with the guideline, we first intravenously administered $1.2 \times 10^{12}$ viral genomes (vg) of AAV-D7 to male ALS mice that as a group were at an early symptomatic stage as reported elsewhere (postnatal day 90, P90; Kondo et al, 2014), and performed histological analyses 30 days later. Note that the forelimb grip strength of the control and AAV-D7 treatment groups of ALS mice was significantly weaker than wild-type (WT) mice at P84 (before treatment), confirming that these ALS mice, as a group, were already at an early symptomatic stage (Fig 1A). Also, we confirmed that the hSOD1-G93A transgene copy number, substantial variation in which might affect disease progression (Pérez-García & Burden, 2012), was comparable in both groups of ALS mice (Fig 1B). In these model mice, AAV-D7 treatment robustly enhanced MuSK activation, as judged by phosphorylation of MuSK and acetylcholine receptor (AChR) in the hind-limb muscle, the latter known to be triggered by activation of MuSK (Fig 1C). To examine histopathology, we first studied NMJs in the diaphragm muscle, where NMJs are particularly amenable to whole-mount imaging due to the muscle’s thin and planar structure (Tetruashvily et al, 2016) and where changes in neuromuscular transmission occur long before motor symptom onset (Rocha et al, 2013). In non-treated ALS mice, although the postsynaptic area characterized by clustered AChRs was not affected, the area of motor nerve terminals was significantly decreased, supporting the neuropathic nature of the defects (Fig 1D–F). However, AAV-D7 treatment significantly increased the area of motor nerve terminals at NMJs, together with the postsynaptic area, indicating positive effects on motor neurons. Indeed, denervation at NMJs was significantly suppressed by the treatment (Fig 1G), although these NMJs showed partial innervation, partly due to the primary enlargement of the postsynaptic area (Fig 1D–F). Together, these findings demonstrate that DOK7 gene therapy protected NMJs from nerve terminal degeneration in ALS mice. Since AAV-D7 expresses human Dok-7 tagged with EGFP, its infection could be monitored (Figs 1D and EV1A–C).

**DOK7 gene therapy suppresses muscle atrophy with no adverse effects on proximal motor neuron degeneration in ALS mice**

Because NMJ defects are thought to be a cause of muscle atrophy in ALS (Pansara et al, 2014), we further evaluated effects of AAV-D7 treatment on muscle fiber size. Analysis of size distribution of the fiber cross-sectional areas (CSA) in tibialis anterior muscle showed that AAV-D7 treatment apparently increased the proportion of myofibers with relatively larger diameter in ALS mice compared with non-treated ALS mice (Fig 2A–C). Consistently, both the cumulative percentage and mean value of CSA showed significant improvement, indicating a beneficial effect of AAV-D7 treatment on muscle atrophy in ALS mice (Fig 2D and E). We also examined the effect of AAV-D7 treatment on progressive motor neuron death, another hallmark of ALS (Yoo & Ko, 2012), and found no significant changes: The number of motor neurons in the ventral horns of the L4-L5 spinal cord segments was comparable between AAV-D7-treated and non-treated ALS mice (Fig EV2A and B). Similarly, proximal axon atrophy was not significantly changed, as the caliber distribution of L4 ventral root axons was comparable between the two groups (Fig EV2C and D). Together, our data indicate that DOK7 gene therapy suppressed NMJ defects and muscle atrophy in ALS mice with no obvious effects on proximal motor neuron degeneration at 30 days postinfection.

**DOK7 gene therapy prolongs life span in ALS mice**

Since an individual patient with ALS is usually diagnosed after onset of symptoms (Zhu et al, 2015), we defined disease onset of each ALS mouse individually as follows, in order to examine the effects of DOK7 gene therapy on life span and motor activity. First, we set the reference points at P84 and P86, within an early symptomatic stage as a group (Fig 1A), to individually obtain a reference forelimb grip strength for each ALS mouse as the mean of those at P84 and P86. Then, disease onset for each ALS mouse was defined as when its forelimb grip strength dropped to 80% or less of its own reference value for two consecutive days, since ALS mice sometimes show ~10% fluctuation even over 2 days. At this individually defined disease onset, we intravenously administered $1.2 \times 10^{12}$ vg of AAV-D7 into each given male ALS mouse to perform survival analysis according to the guideline for preclinical ALS studies (Ludolph et al, 2010), which requires a minimum of 12 mice of a single gender and of comparable hSOD1-G93A transgene copy number for each test or control group. Note that this guideline was recently established for better translation into humans, mainly because many, if not all, clinical trials had failed to translate beneficial life span effects in ALS mice into humans (Genc & Ozdinler, 2014). Remarkably, a study using experimental settings that fit this guideline recently reported that even the FDA-approved riluzole failed to prove its efficacy in ALS mice (Jablonski et al, 2014). However, DOK7 gene therapy significantly prolonged life span of ALS mice (166.3 ± 3.2 days) compared with non-treated ALS mice (154.4 ± 2.7 days; Fig 3A). This therapy also
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prolonged duration of survival after ALS onset (64.2 ± 3.3 days) compared with non-treated mice (50.3 ± 3.1 days; Fig 3B). Neither the age nor the grip strength at disease onset was statistically different between AAV-D7-treated and non-treated groups (Fig 3C and D). In addition, the hSOD1-G93A transgene copy number was comparable between these groups (Fig 3E). We also confirmed that treatment with AAV-EGFP did not significantly alter either the survival (162.1 ± 2.5 days) nor duration after onset (59.8 ± 3.0 days) compared with non-treated mice (survival: 158.4 ± 1.9 days, duration after onset: 57.3 ± 2.4 days), showing that neither AAV infection nor EGFP expression had any obvious effect on survival (Fig EV3A–E). Note that DOK7 gene therapy did...
not affect degeneration of motor neuron cell bodies even at end stage (P150) in ALS mice (Fig EV4A and B), implying that the protective effect of this therapy may be confined distally at the NMJ. This is apparently consistent with the reports that degeneration of motor nerve terminals at NMJs occurs independently of motor neuron cell death (Kostic et al., 1997; Gould et al., 2006; Parone et al., 2013). In
Figure 3. DOK7 gene therapy enhances life span and motor activity in ALS mice.

A–E: ALS mice treated or not with $1.2 \times 10^{12}$ vg of AAV-D7 at individually defined disease onset were subjected to the following assays. Kaplan–Meier survival curves after birth of untreated ALS mice ($n = 14$, $154.4 \pm 2.7$ days, mean ± SEM) and AAV-D7-treated ALS mice ($n = 24$, $166.3 \pm 3.2$ days). $P = 0.0052$ by log-rank test. NT, not treated (A). Kaplan–Meier survival curves after onset in untreated ALS mice ($n = 14$, $50.3 \pm 3.1$ days, mean ± SEM) and AAV-D7-treated ALS mice ($n = 24$, $64.2 \pm 3.3$ days). $P = 0.0023$ by log-rank test (B). Ages at onset for untreated (n = 14 mice) and AAV-D7-treated ALS mice (n = 24 mice). Mean ages of onset were indicated by horizontal bars. Values are means ± SEM. n.s., not significant by Student’s t-test (C). Forelimb grip strength of ALS mice at onset in untreated (n = 14 mice) and AAV-D7-treated groups (n = 24 mice). Values are means ± SEM. n.s., not significant by Student’s t-test (D). The difference in cycle threshold (ΔCt) between the human SOD1-C93A transgene and the reference mouse apob gene. To calculate the human transgene level, the ΔCt value of hSOD1 was subtracted from the ΔCt value of apob (ALS-NT, n = 14 mice; ALS-AAV-D7, n = 24 mice) (E).

F, G: WT or ALS mice treated with $1.2 \times 10^{12}$ vg of AAV-EGFP or AAV-D7 at individually defined disease onset were subjected to the open field tests at the indicated ages (n = 6 or 9 mice). Spontaneous motor activity was represented by locomotor activity (F) and mean speed (G). Values are means ± SEM. (F) *$P = 0.0244$, (G) *$P = 0.0349$ by Mann–Whitney U-test.
addition, although we mentioned above that DOK7 gene therapy might counteract size reduction of the motor nerve terminals at NMJs in ALS mice, there remains the possibility that this therapy might also facilitate reinnervation by remaining motor neurons. Thus, it is important to investigate how DOK7 gene therapy inhibits degeneration of the motor nerve terminals in ALS mice.

**DOK7 gene therapy improves motor activity in ALS mice**

Although we monitored the grip strength of individual mice up to 152 days of age, the data fail to show a significant difference between AAV-D7-treated and non-treated ALS mice (Fig EV4C). However, as AAV-EGFP-treated ALS mice entered late- to end-stage disease, the contrast in spontaneous motor activity with AAV-D7-treated mice was striking (Movie EV1). Thus, we used the automated home cage behavioral system to measure stress-independent spontaneous motor activity (Hayworth & Gonzalez-Lima, 2009; Ludolph et al., 2010). The data show an increase resulting from AAV-D7 treatment throughout the testing period and demonstrate that DOK7 gene therapy significantly improved locomotor activity and speed compared with AAV-EGFP-treated mice at P155 (Fig 3F and G).

**Discussion**

Accumulating evidence demonstrates that defects in NMJs are associated with various types of neuromuscular disorders, including myasthenia, motor neuron degeneration, and sarcopenia, an age-related muscle atrophy (Deschenes et al., 2010; Murray et al., 2010; Sleigh et al., 2014). For example, patients with ALS, including one carrying a SOD1 mutation, manifested NMJ defects, even when biopsied at the early symptomatic stage (Bruneteau et al., 2015). Consistent with this, mouse models of ALS with SOD1, TDP43, FUS, or C9ORF72 mutations also display NMJ defects (Dadon-Nachum et al., 2011; Arnold et al., 2013; Liu et al., 2016; Sharma et al., 2016). In addition, mouse models of neurodegenerative diseases including spinal muscular atrophy and Charcot–Marie–Tooth disease type 2D show NMJ abnormalities (Murray et al., 2010; Sleigh et al., 2014). Furthermore, denervation at the NMJ occurs before myofiber atrophy in sarcopenia model rats (Deschenes et al., 2010), highlighting the NMJ as an attractive therapeutic target. As mentioned, we previously demonstrated that DOK7 gene therapy activates muscle-specific kinase MuSK to enlarge NMJs, and ameliorates myopathies characterized by NMJ defects in mouse models irrespective of the presence or absence of a dok-7 gene mutation, attesting to its potential in a range of neuromuscular diseases (Arimura et al., 2014). However, DOK7 gene therapy has not previously been demonstrated to be effective in motor neuron diseases. Here we demonstrated that a single-dose treatment of AAV-D7 after individually defined disease onset improved life span and motor activity in ALS mice, although the mechanisms by which DOK7 gene therapy suppresses denervation at the NMJ, and disease progression in ALS, remain to be established. Given that EGFP fluorescence from AAV-D7-infected cells was detectable however weakly and faintly in the spinal cord and cerebellum, respectively, in AAV-D7-treated mice (Fig EV1B and C), skeletal muscle-specific transduction of DOK7 will be necessary to completely exclude the possible contribution of non-muscle transgene expression. In addition, to clarify the therapeutic effects of NMJ protection on muscle weakness, electrophysiological study of affected muscle will be essential.

A few studies have evaluated the effect of NMJ preservation on ALS. The expression level of Nogo-A, an inhibitor of neurite outgrowth, is elevated in ALS (Jokic et al., 2005), and its genetic depletion delays denervation at NMJs and prolongs life span in ALS model mice (Jokic et al., 2006). Consistent with this, treatment with anti-Nogo-A antibody improved muscle innervation and motor function in ALS model mice. However, its effect on survival was not shown (Bros-Facer et al., 2014). Moreover, therapeutic treatment with anti-Nogo-A antibody (Ozanezumab) did not show any benefits for ALS patients in a phase II clinical trial (Meininger et al., 2017). In addition, mislocalization of MuSK was reported in SOD1-G93A ALS model mice (Vilmont et al., 2016), and a transgene that modestly increases MuSK expression in muscle from the embryonic stage delayed denervation at NMJs and improved motor function but failed to increase survival of ALS mice (Pérez-García & Burden, 2012). Nevertheless, the effect of ectopic MuSK expression induced after disease onset is not known, and inborn higher-level expression of MuSK in the muscle has been shown to induce scattered NMJ formation throughout myofibers and cause severe muscle weakness (Kim & Burden, 2008), suggesting that forced MuSK expression is not suitable as a therapeutic method. By contrast, we previously showed that DOK7 gene therapy greatly facilitates NMJ enlargement in the appropriate central region of myofibers without lethal effects for more than 1 year in DOK7 myasthenia model mice (Arimura et al., 2014), suggesting that DOK7 gene therapy is a safer therapeutic approach.

Our findings demonstrate that DOK7 gene therapy has potential for treating various motor neuron diseases that manifest NMJ defects. Pharmacological enlargement of NMJs might also be useful. Because previous studies have shown that degeneration of motor nerve terminals at NMJs occurs independently of motor neuron cell death in ALS model mice as mentioned above (Kostic et al., 1997; Gould et al., 2006; Parone et al., 2013), these NMJ-targeted therapies might be more effective when used in combination with other therapies such as those aimed at promoting motor neuron survival.

**Materials and Methods**

**Mice**

The animal studies were performed in accordance with the University of Tokyo guidelines for animal care and use, and approved by the institutional animal care and use committee. Transgenic mice expressing human SOD1 (hSOD1) with the ALS-linked G93A mutation (B6. Cg-Tg[SOD1-G93A]1Gur/J, Stock No. 004435) were purchased from The Jackson Laboratory and bred on the C57BL/6J background, and male mice were used in this study. All mice used in this study were housed on a 12-h light/dark cycle in specific pathogen-free conditions with free access to water and standard mouse chows in the animal facility of the Institute of Medical Science, the University of Tokyo.

**Evaluation of hSOD1-G93A transgene copy number**

Changes in the transgene copy number were estimated using real-time quantitative PCR by determining the difference in cycle
threshold (ΔC) between the transgene (hSOD1-G93A) and a reference gene (mouse apob), according to the recommendation by The Jackson Laboratory. SYBR Premix Ex Taq II (Takara Bio) was used for real-time amplification of DNA. Specific primers for hSOD1-G93A and apob sequences were as follows (5′ to 3′): GGGAAGCTTGGTGCTCAAG (hSOD1-G93A, forward), CAAGGGAGGTAAAAGAAGCACGTGGTCCTCAGCAT (apob, forward), and TCACAGGTCATTTCTGCTTTTG (apob, reverse).

**AAV production**

The cDNA encoding EGFP or human Dok-7 cDNA tagged with EGFP was cloned into pAAV-MCS (Agilent Technologies), which carries the cytomegalovirus promoter, to obtain pAAV-EGFP or pAAV-Dok-7-EGFP plasmid (Arimura et al., 2014). For production of AAV-EGFP or AAV-D7, HEK293T or HEK293EB cells were co-transfected with the AAV9 chimeric helper plasmid pRep2Cap9, the adenovirus helper plasmid pHelper (Agilent Technologies), and pAAV-EGFP or pAAV-Dok-7-EGFP in a HYPERFlask vessel (Corning) using polyethylenimine and cultured for 5 days (Matsushita et al., 2004; Lin et al., 2007). The AAV particles were purified by density-gradient ultracentrifugation (Tomono et al., 2016). The viral titers were determined by real-time quantitative PCR using AAVpro Titration Kit (Takara Bio) with specific primers for the AAV9 sequence as follows (5′ to 3′): CTGACGAAAGGCGCAGGAG (forward) and GTGGTGCAGGACCAATTTTGG (reverse).

**In vivo AAV injection**

1.2 × 10^12 vg of AAV-D7 or AAV-EGFP was intravenously injected by a single shot via the tail vein at a symptomatic stage (P90) or individually defined disease onset. Note that we used wild-type or ALS mice without any treatment, even sham injection, as the control “non-treated mice” or “WT-NT” or “ALS-NT”.

**Immunoprecipitation and immunoblotting**

Whole-tissue lysates (WTLs) were prepared from the hind-limb muscle with alkaline lysis buffer [50 mM Tris–HCl (pH 9.5), 1% sodium deoxycholate, protease inhibitors (Complete, Roche), and phosphatase inhibitors (PhosSTOP, Roche)]. For immunoprecipitation, WTLs were incubated with antibodies to MuSK (C-19 and N-19) or AChRβ1 (H-101) (1:100, Santa Cruz Biotechnology), followed by incubation with protein G-Sepharose (GE Healthcare). For immunoblotting, immunoprecipitates or WTLs were applied to SDS–PAGE, and transferred to a polyvinylidene fluoride (PVDF) microporous membrane (Merck Millipore). The membranes were probed with primary antibodies for phosphotyrosine (4G10; 1:5,000, Merck Millipore), Dok-7 (A-7), AChRβ1 (H-101) (1:2,000, Santa Cruz Biotechnology), MuSK (AF562; 1:2,000, R&D Systems), hSOD1 (#2770), or GAPDH (#2118; 1:2,000, Cell Signaling Technology), followed by incubation with secondary horseradish peroxidase-labeled antibodies anti-mouse IgG (1:10,000, GE Healthcare), anti-rabbit IgG (1:10,000, GE Healthcare), anti-goat IgG (1:10,000, Santa Cruz Biotechnology), or TrueBlot anti-rabbit IgG antibodies (1:2,000, Rockland). The blots were visualized using a LAS4000 imager with ECL Prime Western Blotting Detection Reagent (GE Healthcare). The experiment was repeated four times independently.

**Whole-mount staining of NMJs**

Diaphragm muscles were fixed in 1% paraformaldehyde (PFA) in phosphate-buffered saline (PBS) overnight at 4°C and then rinsed with PBS. The muscles were permeabilized with 1% Triton X-100 in PBS, and incubated with anti-synapsin-1 (#5297) rabbit monoclonal antibodies (1:1,000, Cell Signaling Technology) followed by incubation with Alexa 647-conjugated anti-rabbit IgG (1:2,000, Thermo) and Alexa 594-conjugated α-bungarotoxin (1:2,000, Thermo). Confocal Z serial images were collected with an FV1000 Confocal Laser Scanning Microscope (Olympus) and collapsed into a single image. Images were captured with the same settings and exposure time in each experimental group for comparison. The size (area) and number of presynaptic motor nerve terminals and postsynaptic AChR clusters were quantified using cellSens Digital Imaging Software (Olympus). For quantification, seven microscopic fields with the 20× objective were chosen at random on the diaphragm muscle from each mouse, and 170–260 synaptic sites were analyzed per mouse. These experiments were conducted in a blinded fashion.

**Quantification of myofiber size**

Tibialis anterior (TA) muscles were fixed in 4% PFA in PBS and embedded in paraffin wax. Transverse sections of TA muscle were prepared at 7 μm thickness and subjected to hematoxylin and eosin (H&E) staining. Bright-field images of muscle bundles were collected with a BioREVO fluorescent microscope (Keyence). Cross-sectional area of TA muscle fiber was measured by cellSens Digital Imaging Software. For quantification, at least 450 myofibers per mouse were analyzed. These experiments were conducted in a blinded fashion.

**Visualizing of Dok-7-EGFP expression in vivo**

Mice were transcardially perfused with 4% PFA in PBS under deep isoflurane anesthesia. The brain, spinal cord, tibialis anterior muscle, extensor digitorum longus muscle, soleus muscle, and diaphragm muscle were excised, postfixed overnight in 4% PFA in PBS, and placed in 15% sucrose PBS solution overnight and then in 30% sucrose PBS mixture of 30% sucrose PBS and Tissue-tek O.C.T. Compound (Sakura Finetek). Transverse (muscle or spinal cord) or sagittal (brain) sections were prepared at 20 μm thickness and mounted with VECTASHIELD Hard Set Mounting Medium with DAPI (H-1500, Vector Laboratories, Inc.). Images were collected with an FV1000 confocal laser scanning microscope, and this imaging was performed with the same settings and exposure time for comparison. Data are representative of at least three mice.

**Quantification of motor neuron number**

Mice were transcardially perfused with 4% PFA in PBS under deep isoflurane anesthesia. The spinal cord lumbar region was excised, postfixed overnight in 4% PFA in PBS, and embedded in paraffin wax. Transverse sections of the L4-L5 spinal segment were prepared at 5 μm thickness and stained with cresyl violet (Nissl staining). Bright-field images of spinal cord sections were collected with a BioREVO fluorescent microscope. The number of motor neurons in the ventral horn was counted using cellSens Digital Imaging...
Software, and at least 20 sections were counted per mouse. The following criteria were used to count motor neurons: (i) cells located in the ventral horn, and (ii) cells with a maximum diameter of 20 μm or more (Cai et al., 2015). These experiments were conducted in a blinded fashion. Note that we validated this method by comparing the motor neuron number in wild-type or ALS mice at P120 (Fig EV2B) with those reported elsewhere (Yoo & Ko, 2012).

Quantification of motor axon diameter

L4 ventral roots were frozen in Tissue-tek O.C.T. Compound. To visualize motor axons, transverse sections of L4 ventral roots were prepared at 5 μm thickness and stained with anti-neurofilament-H rabbit polyclonal antibodies (AB1991; 1:2,000, Merck Millipore) followed by incubation with Alexa 594-conjugated anti-rabbit IgG (1:2,000, Thermo). Images were collected with a BioREVO fluorescence microscope, and this imaging was performed with the same settings and exposure time for comparison. Axonal diameters of L4 roots were measured by cellSens Digital Imaging Software. These experiments were conducted in a blinded fashion.

Grip strength test and onset definition

Forelimb grip strength of each mouse was measured using a computerized electronic pull-strain gauge 1027DSM (Columbus Instruments) as described previously (Eguchi et al., 2016). Five measurements were taken per mouse, and the mean of these five measurements was used for statistical analysis. These experiments were conducted in a blinded fashion. To individually define disease onset, the reference forelimb grip strength of each ALS mouse was set as the mean of its strength values at P84 and P86; then, the onset was defined as when its grip strength dropped to 80% or less of its own reference strength for two consecutive days. We measured forelimb grip strength of each mouse every 2 days, unless two-consecutive-day measurements were required to define the onset.

Open field test

Spontaneous motor activity was monitored in the IR Actimeter system (Panlab/Harvard Apparatus). For each measurement, a mouse was placed in the test cage (155 × 245 × 148 mm) for 5 min before recording in order to avoid any bias due to stress. Then, its movement was automatically recorded for 10 min by infrared capture. We analyzed the locomotor activity (counts) and mean speed (cm/s) using the Actitrack software (Panlab/Harvard Apparatus). These experiments were conducted in a blinded fashion.

Statistical analysis

Data were analyzed using JMP Pro 12 (SAS Institute Inc.) or Easy R software. Values are presented as means ± SEM or ± SD. Statistical differences between two groups were determined using the two-tailed Student’s t-test for normally distributed data with comparable variances. The Kolmogorov–Smirnov test was used for comparisons of two cumulative curves. Data sets containing more than two groups were tested using analyses of variance (ANOVA) and Bonferroni or Dunnett’s post hoc test. The nonparametric Mann–Whitney U-test was used for data that were not normally distributed or when a normality test could not be applied. Statistical differences in cumulative survival were determined using the log-rank test. P < 0.05 was considered statistically significant.

Expanded View for this article is available online.

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Author contributions

SM, TTe, SA, and YY designed research. SM and SA performed research. SM, TTo, and TO contributed to AAV production. SM, TTe, SA, TO, and YY analyzed data. SM, TTe, and YY wrote the manuscript.
Conflict of interest

The authors declare that they have no conflict of interest.

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