Overexpression of wild-type androgen receptor in muscle recapitulates polyglutamine disease

Douglas Ashley Monks*,†, Jamie A. Johansen*, Kaiguo Mo‡, Pengcheng Rao‡, Bryn Eagleson§, Zhigang Yu¶, Andrew P. Lieberman§, S. Marc Breedlove*†, and Cynthia L. Jordan*†

*Neuroscience Program and †Department of Psychology, Michigan State University, 108 Giltner Hall, East Lansing, MI 48824; ‡Department of Psychology and Institute of Medical Science, University of Toronto, Mississauga, ON, Canada L5T 1C6; §Van Andel Institute, Grand Rapids, MI 49503; and ¼Department of Pathology, University of Michigan, Ann Arbor, MI 48109

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We created transgenic mice that overexpress WT androgen receptor (AR) exclusively in their skeletal muscle fibers. Unexpectedly, these mice display androgen-dependent muscle weakness and early death, show changes in muscle morphology and gene expression consistent with neurogenic atrophy, and exhibit a loss of motor axons. These features reproduce those seen in models of Kennedy disease, a polyglutamine expansion disorder caused by a CAG repeat expansion in the AR gene. These findings demonstrate that toxicity in skeletal muscles is sufficient to cause motoneuron disease and indicate that overexpression of the WT AR can exert toxicity comparable with the polyglutamine expanded protein. This model has two clear implications for Kennedy disease: (i) mechanisms affecting AR gene expression may cause neuromuscular symptoms similar to those of Kennedy disease and (ii) therapeutic approaches targeting skeletal muscle may provide effective treatments for this disease.

Kennedy disease | neuromuscular | skeletal muscle | spinal and bulbar muscular atrophy | axonopathy

A polymorphism in exon 1 of the androgen receptor (AR) gene, consisting of a variable number of glutamine (Q) repeats, affects AR function. Very long polyglutamine repeat (polyQ) tracts are associated with a progressive neuromuscular disease known as Kennedy disease (KD, or spinal bulbar muscular atrophy) (1). The etiological mechanism mediating polyQ toxicity is uncertain, but is generally thought to confer novel toxic functions to the protein, because expansion of polyQ tracts beyond 40 repeats in other proteins also cause neurodegenerative disease, including Huntington’s disease (HD), and several autosomal dominant forms of spinocerebellar ataxia (SCA) (2). Histopathological studies of KD patients suggest “neurogenic” responses to denervation, and the etiology of this disease is therefore generally thought to begin with motoneuron pathology (3).

Explicit mouse models of KD, in which polyQ AR alleles containing 60 CAG repeats or more are expressed, develop a disease phenotype that includes a marked reduction in body weight, kyphosis, and striking deficits in muscle strength and motor coordination (4–8). Androgen dependence, motoneuron and muscle pathology, and/or inclusions containing AR are also observed in these models (4, 5, 7, 8). Our studies of AR in skeletal muscle (9, 10) led us to generate transgenic (Tg) mice in which AR is overexpressed solely in skeletal muscle fibers using an expression cassette containing the human skeletal α-actin (HSA) promoter. We discovered a striking phenotypic resemblance between these HSA-AR mice and mouse models of KD. This similarity is surprising given that the Q repeat in this AR transgene comprises only 22 glutamines and is expressed exclusively in skeletal muscle fibers and not in motoneurons.

Results

HSA Promoter Drives Transgene Expression Exclusively in Skeletal Muscle Fibers. We first validated our HSA expression cassette by generating HSA-LacZ. (LacZ = β-galactosidase gene) reporter mice [supporting information (SI) Fig. 5A]. Consistent with other expression cassettes containing the HSA promoter (11, 12) these reporter mice express β-gal specifically in skeletal muscle fibers, starting at embryonic day 9.5–10.5, with no detectable expression in other tissues, including the heart, viscera, fat or spinal cord (SI Fig 5B and C). We also created Tg mice in which a rat WT AR cDNA is driven by this same HSA expression cassette (SI Fig 6A), resulting in selective overexpression of AR in skeletal muscle fibers but not in other cell types within muscle (HSA-AR Tg mice; SI Fig 6B). As further validation of the specificity of transgene expression, we crossed our HSA-AR mice with AR mutant [testicular feminization mutation (Tfm)] mice. Tfm males express little to no AR protein (13), offering a null background for AR in which to assess AR transgene expression. As expected, Western blots of tissues from such Tfm/HSA-AR male progeny revealed AR in skeletal muscle, and essentially none in spinal cord, testes, or heart (SI Fig. 6C). Furthermore, immunostaining revealed that lumbar motoneurons of HSA-AR/Tfm male mice contain no AR immunoreactivity, comparable with Tfm male mice, but in striking contrast to the robust AR staining in motoneuronal nuclei of WT male mice (SI Fig. 7). These data provide clear evidence that the HSA-AR transgene is not expressed in spinal motoneurons. Taken together, these data demonstrate that the HSA-AR transgene results in specific overexpression of AR in skeletal muscle fibers and not elsewhere. Despite prominent nuclear staining for AR in muscle fibers (SI Fig 6B) of HSA-AR Tg male mice, we find no clear evidence of AR-positive aggregates.

Overexpression of AR in Skeletal Muscle Fibers Causes Androgen-Dependent Motor Dysfunction and Early Death. We detected transgene expression in seven founding lines of HSA-AR Tg mice and selected two (L78 and L141) for in-depth characterization. These lines differ in transgene copy number (L78 < L141) and have corresponding differences in transgene expression as indicated by muscle AR mRNA (SI Fig 6E) and protein (SI Fig 6F). Reduced


Conflict of interest statement: D.A.M., S.M.B., and C.L.J. have filed a patent concerning the role of muscle fiber androgen receptor in neuromuscular disease.

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Abbreviations: AChR, acetylcholine receptor; AR, androgen receptor; HD, Huntington’s disease; HSA, human skeletal α-actin; KD, Kennedy disease; L78, founding line 78 transgenic mice; L141, founding line 141 transgenic mice; LacZ, β-galactosidase gene; MyoD, myogenic differentiation gene; polyQ, polyglutamine repeat; Tfm, testicular feminization mutation; Tg, transgenic; EDL, extensor digitorum longus; T, testosterone.

To whom correspondence should be addressed: Neuroscience Program and Department of Psychology, Michigan State University, 108 Gilfert Hall, East Lansing, MI 48824. E-mail: jordancy@msu.edu.

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male viability at birth was observed for Tg males but not Tg females in all seven lines (survival data for L78 and L141 in SI Table 1). Treatment of pregnant dams with the anti-androgen flutamide enhances perinatal survival of Tg males (data not shown), suggesting perinatal death of Tg males depends on prenatal androgen exposure and not overexpression per se of the AR protein. The absence of perinatal mortality in Tg females (SI Table 1) also supports this conclusion.

Surviving Tg males of three founding lines (including L141) have a marked phenotype suggestive of motoneuron disease, including kyphosis (Fig. 1A), reduced body weight (Fig. 1B), and striking deficits in muscle strength and motor function (Fig. 1C and D). Despite showing somewhat lower body weights, surviving Tg males of the remaining four lines (including L78) are comparable with WT brothers in motor function (Fig. 1C and D). Given that transgene expression, at both the mRNA and protein levels, is higher in muscles of symptomatic L141 mice than in muscles of asymptomatic L78 mice, these data indicate that AR expression levels correspond to phenotypic severity. We also find that the loss of motor function is androgen-dependent in Tg males. Castration of adult L141 Tg males dramatically improves their motor function (Fig. 1E and SI Movie 1).

In contrast to the obvious phenotype of Tg males, Tg females from all lines appeared unaffected by expression of the AR transgene. In addition to showing normal viability perinatally, they also showed no loss of motor function as adults (untreated TG/VEH groups in Fig. 2). However, when we treated adult Tg females with exogenous testosterone (T) that approximated normal male levels of circulating T (data not shown), several aspects of the male phenotype were rapidly induced in L141 Tg females, including weight loss and motor deficits (Fig. 2). Notably, such females show significant deficits in hang time before losses in body weight, suggesting that motor deficits precede overt muscle atrophy. We learned that >9 days of T treatment is fatal to L141 Tg females. On the other hand, L78 Tg females do not become obviously atrophic with T treatment, even when the T treatment is extended to several weeks (data not shown), nor do they show any motor dysfunction (data not shown).

**Skeletal Muscles of HSA-AR Tg Male Mice Show Pathology Consistent with Motoneuron Disease.** These features of impaired motor function, reduced body weight and androgen dependence are akin to KD. To explore this idea further, we examined cross sections of the extensor digitorum longus (EDL) for pathology using H&E and NADH (Fig. 3A) stains. L141 Tg male mice showed abnormalities consistent with a KD phenotype, including both atrophic and hypertrophic fibers, internal myonuclei, fiber splitting, altered myofibrillar organization, and an overall increase in oxidative metabolism. No lymphocytic infiltrate or other histological signs of inflammation were present in the muscle. L141 Tg males also have nearly half the number of EDL fibers compared with WT controls (Fig. 3B), with average fiber size slightly smaller than in WT controls (mean ± SEM: WT = 1.479 ± 92.2 μm², Tg = 1.308 ± 92.5 μm²) but not significantly different.

This difference in fiber number could reflect muscle fiber loss due to apoptosis, but we find no evidence of pycnosis in H&E stained muscle sections. Another possibility is that T produced by the testes prenatally interferes with myogenesis such that Tg males never achieve the normal adult number of muscle fibers. This possibility seems unlikely, however, because Tg males exposed to flutamide during late gestational myogenesis, still

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**Fig. 1.** Phenotype of HSA-AR male mice. (A) Photograph of L141 Tg male and age matched WT brother (top). L141 Tg males have reduced body weight (A and B), marked kyphosis (A) and motor deficits as revealed by paw print records (C) and the hang test (D). Despite reduced body weight, motor deficits are not observed in L78 Tg males, which express the AR transgene at a lower level than affected L141 Tg males (see SI Fig. 6). Castrating L141 Tg males reverses deficits in hang time (E). Graphs represent mean ± SEM, open bars represent Tg males, and filled bars represent WT controls. *p < 0.05, significantly different from WT controls. WT (78 n = 13, mean age in days: 294, range: 179–528), 78 Tg (n = 14–15, mean age: 281, range: 106–528), WT 141 (n = 12–15, mean age: 131, range: 72–218), Tg 141 (n = 6–7, mean age: 119, range: 72–179). Castrates: WT (n = 3, intact age: 80, castrate age: 90), Tg (n = 3, intact mean age: 74, range: 63–80, castrate mean age: 123, range: 90–190).

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**Fig. 2.** T treatment of asymptomatic 141 Tg females rapidly induces disease symptoms. Percent change relative to initial body weight, stride length during gait analysis, time on the hang test (seconds), and latency to fall on a constant speed rotarod during 9 days of T or vehicle (VEH) treatment of Tg or WT females. Motor dysfunction is therefore androgen-dependent in HSA-AR Tg mice, as in polyQ AR mice. *p < 0.05 lower than Day 0 within a treatment group. Note that only the T-treated Tg females show a significant drop on these measures over time. However, T has no effect on fiber or axon number in L141 Tg females (ANOVA indicates no significant effects of genotype or treatment, or a significant interaction), despite its debilitating effects on motor function. T does not have these effects on body weight or motor function of L78 Tg females (data not shown), paralleling the apparently normal behavioral phenotype of L78 Tg males. Means ± SEM of n = 7 mice/group (mean age/group: 102–103 days old; overall age range: 70–114 days old).
losses in motor function, indicating that motor dysfunction does not depend on muscle fiber loss.

Asymptomatic L78 Tg males also show considerable pathology in the EDL (Fig. 3A), including significantly fewer fibers (Fig. 3B) compared with WT controls, even though motor function seems normal. Pathological changes in muscles from L78 Tg males suggest that either a threshold for such pathology must be reached before motor deficits are apparent or that other factors underlie the loss in function. The fact that T-treated L141 Tg females develop a severe motor deficit without any loss of fibers supports the latter possibility.

**Axonopathy but Not Loss of Motoneuronal Cell Bodies in Symptomatic Tg Male Mice.** Because several neuromuscular diseases, including ALS and KD are associated with a loss of motoneurons and/or motor axons at autopsy, we counted the number of motor axons in lumbar (L) ventral roots 4 and 5 and Nissl-stained motoneurons in 3 lumbar motor pools [the spinal nucleus of the bulbocavernosus (SNB), the dorsolateral nucleus (DLN), and the retrodorsal lateral nucleus (RDLN)]. We found symptomatic L141 Tg males have significantly fewer L5 motor axons than age-matched WT controls (Fig. 3 C and D), although the number and size of motoneuronal somata are unaffected in these same mice (SI Table 2). Counts of the number of motor axons in L4 also indicate a significant deficit in Tg L141 males compared with their WT controls [mean ± SEM: WT = 698 ± 31.92 (n = 5) vs. Tg = 537 ± 34.82 (n = 4); *P < 0.04]. These data suggest that HSA-AR mice exhibit axonopathy which may precede motoneuron cell death. No difference in average cross-sectional area of surviving axons (mean ± SEM: WT = 45.5 ± 4.43 μm²; Tg = 45.2 ± 8.51 μm²), nor in the size distribution of these axons was observed (data not shown). Notably, axon number was unaffected in asymptomatic L78 Tg males (Fig. 3C), despite significant losses in muscle fiber number, suggesting that axon loss is secondary to muscle pathology. Treatment also did not affect the number of motor axons in L141 Tg females (data not shown), despite its profound effect on motor function. These results indicate that neither motoneuron nor muscle fiber loss are required for motor dysfunction.

**Denervation-Sensitive Genes Change in the Expected Direction in Muscles of Symptomatic but Not Asymptomatic Tg Male Mice.** We next examined genes that are known to be dysregulated in polyQ AR mouse models of KD and/or responsive to denervation, including VEGF, myogenin, acetylcholine receptor (AChR) alpha subunit, and myogenic differentiation (MyoD). Expression of VEGF164 is reduced in a transgenic model of KD (8), whereas both myogenin and AChR are elevated in skeletal muscle of polyQ AR knockin mice (7). We saw similar changes in the expression of these genes, with VEGF164/188 mRNA significantly reduced, and mRNAs for myogenin and AChR significantly increased in muscles from L141 male Tg mice relative to those from WT brothers (Fig. 4). Levels of MyoD mRNA also increased, paralleling changes after denervation (14). No such changes were observed in behaviorally asymptomatic L78 Tg males. These results are consistent with neurogenic atrophy (14, 15) and suggest that HSA-AR and other polyQ AR mouse models share a common molecular etiology. The important distinction however between our model and others is that our experimental gene is expressed only in skeletal muscles, indicating that such indices of neurogenic atrophy can result from processes that originate in muscle.

**Discussion**

The nature of the observed phenotype bears a striking resemblance to mouse models of KD, which also exhibit androgen-dependent motor dysfunction (4, 5, 7, 8). The loss of motor axons in HSA-AR mice is consistent with human KD patients and shows a significantly reduced number of muscle fibers in adulthood compared with their WT littermates (data not shown). More studies would be needed to clarify this issue. Surprisingly, L141 Tg females treated acutely with T in adulthood show no such deficit in muscle fibers (data not shown), despite profound

*Fig. 3.** Histopathology in HSA-AR Male Mice. (A) Photomicrographs illustrating histopathology in EDL muscle sections stained with H&E or NADH from a WT male, or L78 or L141 Tg males. Muscle pathology seen in L78 and L141 Tg males is typical of that seen in KD, including grouped atrophic fibers (arrowheads), centralized nuclei (arrows), and increased NADH staining. Muscle pathology is notably greater in the symptomatic L141 Tg males compared with their WT controls [mean ± SEM: WT = 698 ± 31.92 (n = 5) vs. Tg = 537 ± 34.82 (n = 4); *P < 0.04]. These data suggest that HSA-AR mice exhibit axonopathy which may precede motoneuron cell death. No difference in average cross-sectional area of surviving axons (mean ± SEM: WT = 45.5 ± 4.43 μm²; Tg = 45.2 ± 8.51 μm²), nor in the size distribution of these axons was observed (data not shown). Notably, axon number was unaffected in asymptomatic L78 Tg males (Fig. 3C), despite significant losses in muscle fiber number, suggesting that axon loss is secondary to muscle pathology. Treatment also did not affect the number of motor axons in L141 Tg females (data not shown), despite its profound effect on motor function. These results indicate that neither motoneuron nor muscle fiber loss are required for motor dysfunction.

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**Discussion**

The nature of the observed phenotype bears a striking resemblance to mouse models of KD, which also exhibit androgen-dependent motor dysfunction (4, 5, 7, 8). The loss of motor axons in HSA-AR mice is consistent with human KD patients and
many mouse models of KD (3, 4, 6, 8, 16). We also observed
dysregulation of gene expression reported in several polyQ mouse models (7, 8). Whereas we did not observe AR-containing nuclear aggregates in muscle fibers or motoneurons of Tg male mice of either line, the role of aggregates in many neurodegenerative diseases, including polyQ diseases, remains controversial (17, 18). The similarities in pathology between KD and HSA-AR mice are surprising because the HSA-AR transgene is expressed exclusively in skeletal muscle fibers and contains only 22 glutamine repeats, well within the WT range (SI Fig 6A, verified by sequencing in all founding lines of HSA-AR Tg mice).

These results raise the intriguing question of how a protein that typically promotes anabolic responses in muscle can result in atrophy and neurodegeneration when overexpressed. Whereas an answer to this question is not yet available, molecular chaperones and the ubiquitin-proteasome pathway may be involved. A related question is whether overexpression of any protein in muscle fibers would be toxic. Several observations argue against this possibility. First, we find no evidence for pathology in >12 lines of HSA-LacZ mice that express β-gal in their muscle fibers (SI Fig 5), nor for mice that express Cre recombinase driven by HSA in muscle fibers (data not shown). Second, it is not simply expression level of AR that confers pathological properties in HSA-AR mice, as females must be treated with androgens before showing motor dysfunction. Moreover, perinatal survival of Tg males can be significantly enhanced by prenatal exposure to the anti-androgen flutamide. Finally, castration of adult Tg males largely reverses the loss of function (see SI Movie 1). Thus, in several different contexts, we find that AR becomes toxic only once activated by hormonal ligand, rather than because of overexpression per se of the protein.

However, it also worth noting that our model is not the first to show that overexpression of a WT protein seems capable of exerting toxicity comparable with the mutant disease version of the protein. Other examples include ataxin-1 (19, 20), α-synuclein (21), and tau (22). Remarkably, for each “disease” protein, overexpression of the WT form induces a comparable neurodegenerative phenotype as the mutant allele. For example, overexpression of WT ataxin-1 causes neurodegeneration in Drosophila and mouse models of spinal and cerebellar ataxia 1 (SCA1) (19, 20), suggesting that an expanded polyQ tract is not necessary for toxicity and may be only one of several ways toxicity is conferred to a protein. Similarly, in Drosophila models of tauopathy, overexpression of WT tau is sufficient to induce neurodegeneration (22) and gene duplication of WT α-synuclein causes Parkinson’s disease similar to the mutant form of the protein (21).

Our results also reinforce the potential for myogenic contributions to KD, which has previously been proposed based on observations of AR-containing aggregates in polyQ AR mouse muscle (4). This possibility is also supported by observations that muscle AR aggregates and myopathy significantly precede motoneuron pathology in a polyQ AR knockin mouse model (7). Interestingly, R6/2 HD mice exhibit a progressive neuromuscular pathology that has been ascribed in part to primary actions of the mutant protein on skeletal muscle (23), further suggesting common pathological mechanisms in muscle that may underlie a loss of motor function in several polyQ diseases.

Our male Tg mice display behavioral, neuronal and muscular pathologies that are normally regarded as “neurogenic” in origin. The obviously atrophic appearance of animals, their loss of muscle strength coupled with losses in muscle fiber and axon number as well as the pattern of changes in gene expression in muscles is all consistent with the muscles being denervated. These changes may indeed reflect muscle denervation that is a secondary response to primary changes in the muscle, i.e., changes in the muscle which trigger axon withdrawal and loss. One possible scenario is that a decrease in muscle-derived VEGF may trigger axonopathy in our model. Because VEGF-A, which in mice is comprised mainly of VEGF164 (24), is expressed in the sarcolemma of muscle fibers (25), such a scenario seems plausible.

Symptomatic HSA-AR male mice exhibit significant losses in L4 and L5 ventral root axons but not at the level of motoneuronal cell bodies. Similar “dying back” axonopathies are observed in many, indeed most, models of motoneuron disease, including models of ALS, spinal muscular atrophy (SMA) (26–29), and, notably, KD (3, 5, 7, 30). For example, the SOD1 (G93A), progressive motoneuropathy (pmn) and motoneuron degeneration (Mnd) mouse models all show a loss of synaptic connections before symptoms appear (27). Furthermore, in the SOD1 (G93A) mouse model, degeneration is first seen at the neuromuscular junction, followed by axonal loss and eventually motoneuron loss (28). Additionally, in one model of SMA, a loss of L4 and L5 axons is seen before motoneuron loss, and motor axons are more severely affected than motoneuronal somata by the smn mutation (29). Thus, axonopathy usually precedes cell death, suggesting that motoneurons in HSA-AR male mice might eventually die as part of this process, if the mice were to survive long enough.

Mouse models of KD show similar signs of axonopathy (5, 7, 30), and indeed suggest that axonopathy, rather than cell death, may be a critical event underlying loss of motor function in this disease. A striking example is a recently described KD mouse model (5) that, despite showing profound losses in motor function, shows no evidence of motoneuronal or muscle pathology, including no loss of motoneurons. Such mice did show a change in the phosphorylation status of motoneuronal neuro-
filament proteins, suggestive of axonopathy. In short, results of our model are highly consistent with many other animal models of motoneuron disease, including models of KD, and raise the possibility that changes in muscle gene expression may be sufficient to cause both axonopathy and loss of motor function, and that neither requires motoneuronal cell death.

The relative lack of pathology in our T-treated HSA-AR Tg females despite devastating losses in function is also highly reminiscent of the KD model described above. Both models show an androgen-dependent loss in motor function in the absence of either muscle fiber or motoneuronal loss, suggesting that standard histopathological markers used to diagnose neurodegenerative disease may not necessarily inform us about the mechanisms underlying disease. However, a question raised by our data is whether the disease process is fundamentally the same for HSA-AR Tg males and females, given the fact that symptomatic Tg males exhibit losses in muscle fiber and axon number that symptomatic T-treated Tg females do not. Several observations suggest that the mechanisms triggering a loss of motor function may in fact be the same in the two sexes. For example, T treatment triggers a loss of motor function only for Tg females in L141 and not for Tg females in L78, just as only L141 and not L78 Tg males show deficits in motor function (Fig. 1). Muscles from both Tg males and T-treated Tg females show dysregulation of the same genes in the symptomatic line (L141, data not shown). Therefore, we suspect that the deficits in muscle fiber and axon number exhibited by Tg males but not Tg females reflect differences in the length of androgen exposure—many weeks of androgen exposure culminates in fiber and axonal loss that nine days does not. It is difficult to understand, however, why T treatment of Tg females that results in slightly lower plasma T levels than untreated adult males triggers a much more rapid loss in motor function compared with the slower progression of loss seen in Tg males. It is possible that Tg males, given a prolonged but regulated exposure to androgens, develop protective mechanisms that Tg females simply do not have time to develop.

Our findings call into question whether other disorders regarded as “motoneuron” diseases may actually be muscle diseases that eventually cause motoneuronal pathology. That high levels of WT AR in skeletal muscles can mimic the effects of expanded polyQ AR indicates that expanded polyQ tract is not necessary to induce an androgen-dependent motoneuronal disease and raises the possibility that similar mechanisms may also contribute to KD in humans. Moreover, because an androgen-dependent phenotype is induced by expression of an AR transgene in skeletal muscle fibers, therapeutic approaches targeting muscles and/or neuromuscular junctions may provide effective treatments for Kennedy disease.

In summary, we describe a recently discovered transgenic mouse in which muscle overexpression of AR without polyQ expansion results in neuromuscular atrophy with many key features of KD, including the following: sex-limitation, androgen-dependence, motor deficits, kyphosis, myopathy, motor axon loss, and dysregulation of genes implicated in this disease. These findings further implicate muscle AR in KD and suggest that overexpression of WT AR can recapitulate the pathological consequences of polyQ expansion of AR.

Materials and Methods

Statistical Analysis. Within founding lines, Tg Males were compared with their WT brothers or aged-matched WT males using independent groups t tests with level of significance set at P = 0.05 two-tailed, and n = number of animals in each group. Additional comparisons were occasionally made between L78 and L141 males using independent groups t tests with level of significance set at P = 0.05 as indicated. Females were analyzed using a three-way analysis of variance with treatment (T vs. blank) and genotype (WT vs. Tg) as between subjects factors, and time (day 0–day 9) as a repeated factor. Fisher’s least significant difference post hoc comparisons were used to locate sources of variance.

Generation of Tg Mice. AR cDNA was subcloned from pCMV-AR (kind gift of E. Wilson, University of North Carolina, Chapel Hill, NC) into BlueScript II plasmid (pBS) and the KpnI site of the multiple cloning sequence of the resulting subclone was converted into a NotI site by using oligonucleotide linkers. LacZ was subcloned from pCMV-BGAL (Invitrogen, Carlsbad, CA). Both cDNAs were ligated into the NotI site of pBSX-HSA (kind gift of J. Chamberlain, University of Washington, Seattle, WA). HSA was originally cloned in the laboratory of L. Kedes (31). Tg animals were produced by pronuclear injection of C4 ¥ C57BL/6J zygotes. Tg animals were identified by using PCR amplification of transgene specific regions. Founding Tg animals were mated to C57BL/6J mice, and their progeny were analyzed.

Animal Surgery and Hormone Treatment. Adult Tg and WT female siblings from L141 and L78 were ovarioctomized under isoflurane anesthesia and received s.c. Silastic implants that were empty or filled with T (1.57 mm inner diameter and 3.18 mm outer diameter; effective release length of 6 mm), resulting in low physiological levels found in adult males. Behavior was measured before (day 0), and after surgery. Most animals were killed on day 9, but some T-treated Tg females were killed on day 7 depending on disease progression.

Behavioral Methods. Hang test. Mice were tested for motor function by using the hanging wire test. Mice were placed on a wire grid and turned upside down 40 cm above a counter or cage bedding, and the latency to fall up to 120 s was measured (8).

Paw print analysis. Forepaws were painted with nontoxic acrylic red paint and hindpaws painted with blue. Mice were placed at one end of a piece of paper and guided to walk along it (32). Stride length was measured from fore and hindlimbs and averaged to yield a single estimate per animal.

Rotarod. To test for muscle endurance and motor coordination, mice were tested with a Rotarod (Columbus Instruments (Columbus, OH; axle diameter 3.6 cm; speed of 16 rpm)). Each animal was given three trials with 10 min in between each session, and the test was stopped after 180 s (33). Animals were trained for 1 week before first testing.

Tissue Harvesting and Processing. Under surgical anesthesia, EDL muscles were harvested, weighed, and frozen in OCT-filled cryomolds in liquid nitrogen. EDL muscles were cryostat sectioned at 10 μm and stained for Harris H&E or NADH. Quadriceps were harvested and frozen on dry ice for Western blot analysis. Other tissues were harvested and frozen on dry ice for Southern and Western blot analysis, sequencing, or quantitative real-time RT-PCR. Spinal cords for most animals were immersion fixed ±30 days in 10% buffered formalin for later ventral root harvesting.

Quantitative Real-Time RT-PCR. RNA isolation and cDNA preparation. Total RNA was isolated from limb muscles by using TRIzol and analyzed by using gel electrophoresis and spectrophotometry. Samples were DNase I treated before reverse transcription using a dT20VN primer (Sigma, Oakville, ON) with SuperScript II. Resultant cDNA was diluted 1:8 for future use. Each cDNA reaction had a control reaction without reverse transcriptase (no RT control).

qPCR and analysis. Each 25-μl real-time PCR amplification used 2 μl of the cDNA or no RT control. Reactions were assembled by using SYBR Green JumpStart Taq ReadyMix (Sigma). Primers were as follows: VEGF, atctcaacgctcttg and aatgctttctccgctctgaa;
MyoD, gacagggagggtagg and tctgctcataagg; myogenin, cctagcagcgaactc and aacctggttttcagacat; AChR, cacacagtctga and ttccacattccataaggt; GAPDH caaggtgtagagaag and gaccagcctgctgt.

Samples were incubated at 95°C for 10 min before thermal cycling (40 cycles of: 95°C for 30 s, 57°C for 30 s, and 72°C for 30 s) using the Mx4000 System (Stratagene, La Jolla, CA). Melting curves were determined for all PCR products. The ROX (5-carboxy-X-rhodamine, succinimidyl ester)-normalized fluorescence measurements were analyzed using the LinRegPCR program (34) to correct for efficiency of each reaction. The expression of each test gene was normalized to the level of GAPDH within each.

Morphometrical Analysis. Quantification of muscle number and size. Total fiber number and average fiber size was determined from a cross section of H&E-stained EDL from the middle of the muscle. Every fiber was counted, and the cross sectional area of individual fibers was determined stereologically by using the Stereo Investigator program (MicroBrightField, Burlington, VT). Briefly, the section was outlined at low power, and then muscle fibers were sampled by using a ×40 objective and the “fractionator” probe every 300 μm throughout the cross section. All fibers that intersected the sampling box were measured.

Quantification of axon number and size. L5 ventral roots were harvested from formalin fixed spinal cords, embedded in Poly/Bed Araldite 502, sectioned at 1 μm, and stained with Toluidine Blue by the Michigan State University Electron Microscopy Laboratory. Every myelinated axon was counted in a single cross section, and their size measured as described for fiber size, with the exceptions that a ×63 objective was used and axons were sampled every 100 μm.

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**Supporting Information**

Files in this Data Supplement:

- SI Figure 5
- SI Figure 6
- SI Figure 7
- SI Table 1
- SI Movie 1
- SI Table 2

**SI Figure 5**

**Fig. 5.** Expression of HSA-LacZ transgene. *(A)* HSA-LacZ construct - the human skeletal α actin (HSA) expression cassette drives expression of the LacZ sequence, which codes for β-galactosidase. *(B)* Expression of β-galactosidase in whole neonatal Tg pup is detected histochemically via X-gal, which yields a blue reaction product. A WT littermate stained identically is shown as a control. Note the uniform X-gal staining of Tg skeletal muscle and the absence of ectopic staining in viscera, bone, or adipose tissues. *(C)* Photomicrograph of X-gal staining of cross sections of Tg EDL muscle *(Upper)*, and Tg spinal cord *(Lower)* using Nomarski optics. Note the blue staining in skeletal muscle fibers and absence of blue staining in spinal cord, including motoneurons (arrows).

**SI Figure 6**

**Fig. 6.** Expression of HSA-AR transgene. *(A)* HSA-AR construct. The same HSA expression cassette described for HSA-LacZ mice (see SI Fig 5A) drives expression of a rat androgen receptor (AR) cDNA. The amino acid and nucleotide sequences of the polyglutamine tract are indicated. *(B)* AR immunoreactivity in cross sections of extensor digitorum longus muscle prepared from WT *(Left)* and transgenic (Tg; *Right*) males. Note the increase in AR-immunoreactive nuclei in muscle fibers (arrow) of Tg muscle but not in interstitial nuclei, demonstrating specific overexpression of AR in this cell type. *(C)* Western immunoblot of various tissues from WT, testicular feminization mutant *(Tfm)* mice, which have little to no full-length AR protein, and Tg mice crossed onto the *Tfm* background *(Tfm/Tg)*. Overexpression of AR is observed in skeletal muscle samples but not other tissues from Tg mice, confirming the selective expression of the AR transgene in skeletal muscles. MW, protein standards; S, WT spleen (negative control); VP, WT
ventral prostate (positive control); Q, quadriceps muscle; B, bulbocavernosus/levator ani muscle sample; LMB, lumbar spinal cord; CRV, cervical spinal cord. Western blot methods were as follows. Tissues were homogenized, and centrifuged at 12,000 × g for 5 min; 20 μg of total protein from supernatant was loaded onto 6% or 8% Tris-glycine gel and run at 125 V for 2 h. Proteins were transferred to a nitrocellulose membrane at 45 V for 2 h and probed for AR (N-20, Santa Cruz, 1:500), followed by anti-rabbit-HRP (Santa Cruz, 1:1,000) and detected by Luminol (Santa Cruz). (D-F) Mice from the L141 line, which display marked motor deficits, carry more copies and express transgene mRNA and protein at higher levels than L78 mice, which display a normal behavioral phenotype. Tg males from the L14 line, which was not the focus of this study, also displayed perinatal mortality and severe kyphosis for those few males that survived to adulthood. (D) Southern blot analysis of three founding lines of HSA-AR Tg mice (L78, L14, and L141); each lane is loaded with 25 μg of DNA from three different mice of each line. Known amounts of plasmid DNA were additionally loaded as indicated. Southern blot methods were as follows. Three positive adult animals from each line were used for Southern blot analysis to determine copy number of the transgene. Tissue from kidneys or spleen was homogenized and digested overnight with Proteinase K. DNA was extracted and resuspended in water; 25 μg of each sample and 0.2, 0.04, and 0.02 ng of plasmid DNA were digested with the restriction enzymes KPNl and BamHI, which cut out a 3-kb fragment of the HSA-AR plasmid. The DNA was separated by electrophoresis using a 1% agarose gel. The gel was stained with ethidium bromide and photographed using the Bio-Rad Gel documentation system. Gels were then depurinated in 0.2 M HCL for 10 min, denatured in a solution of 1.5 M NaOH and 0.5 M NaCl for 40 min, and then neutralized in a solution of 1.5 M NaCl, 0.5 M Tris•Cl (pH 7.2), and 0.001 M EDTA. The gels were then blotted overnight onto Hybond n + Nylon Membrane using 20× SSC and exposed to UV light to cross-link the DNA to the membrane. Primers (forward, ctgggttgctactacggagct; reverse, ctggggggttatctggagcc), which amplify a 700-bp fragment of the HSA-AR plasmid, were used to make [32P]dCTP-labeled probe. The membranes were hybridized to the probe for 72 h at 65°C, and blots were washed and exposed to film. The 3-Kb bands of interest were quantified using a phosphorimager (STORM, Amersham Pharmacia). (E) Quantitative PCR estimates of AR mRNA in muscle samples from WT (n = 7), L78 Tg (n = 3), and L141 Tg (n = 4) males. *, All groups significantly differ from one another. The graph represents mean ± SEM. qPCR methods were as follows. To estimate AR transgene expression, qPCR was carried out essentially as described in the text, except a standard curve was used to estimate AR abundance. The standard curve for AR was generated by linear regression of threshold cycle (CT) values for serial 10-fold dilutions of known amounts of AR cDNA. (F) Western immunoblot demonstrating differences in the amount of AR protein between muscle samples from WT, and three sets of different L78 and L141 Tg male mice. Abbreviations and methods as in C.
Androgen receptor (AR) immunoreactivity in spinal cord of Tfm/HSA-AR mice. Although adult WT male mice (A) show robust AR immunoreactivity in nuclei of lateral motoneurons of the lumbar spinal cord, comparably located spinal motoneurons of Tfm male mice expressing the AR transgene in their muscle fibers (B) or of Tfm-only male mice (C) lack such nuclear AR staining, indicating that the HSA-AR transgene is not expressed in spinal motoneurons. Note that the nuclei of WT motoneurons are stained dark (arrow in A) as opposed to the motoneuronal nuclei of Tfm/Tg and Tfm-only male mice that are devoid of such AR immunoreactivity (arrows in B and C, respectively). (Scale bar = 30 μm.) Adult male mice of three different genotypes (WT, Tfm, or Tfm/HSA-AR) were perfused with saline followed by 4% phosphate buffered paraformaldehyde. Tfm and Tfm/HSA-AR mice received s.c. injections of 500 μg of testosterone propionate dissolved in 0.05 ml of sesame oil 1.5-2 h before killing to enhance detection of nuclear AR in spinal motoneurons as Tfm mice have extremely low levels of plasma T, well below normal WT levels (C.L.J., unpublished observation). Spinal cords were harvested, postfixed for 1 h in the same fixative, and then stored overnight at 4°C in 20% phosphate-buffered sucrose. Thirty-micrometer cross sections cut using a freezing sliding microtome were collected in PBS and then stained for AR following a previously published protocol (1). Sections from all three genotypes were stained in a single run using all of the same reagents to avoid introducing artifactual differences. AR-stained sections were then lightly counterstained with the Nissl stain Neutral Red before coverslipping to reveal AR negative motoneurons. Motoneurons in the DLN at a comparable rostrocaudal level of the spinal cord were evaluated for AR-IR for all three genotypes.


**SI Movie 1**

**Movie 1.** Androgen dependence of motor dysfunction in L141 HSA-AR transgenic (Tg) male. In the first segment a Tg male interacts with its much larger WT brother. Note the paucity of locomotion and waddling gait of the Tg male. In the second segment, the Tg male attempts to hold on to a cage top as it is slowly rolled over in the hang test. The male quickly falls off, landing on its back and has difficulty righting itself. In three trials, this Tg male was able to hang on for an average of 1.3 s. When this same male is castrated, it performs well on the hang test 5 days later, holding on for over 60 s.
**Supporting Figure 3: Androgen receptor (AR) immunoreactivity in Spinal Cord of Tfm/HSA-AR mice**

Although adult wt male mice (A) show robust AR immunoreactivity in nuclei of lateral motoneurons of the lumbar spinal cord, comparably located spinal motoneurons of Tfm male mice expressing the AR transgene in their muscle fibers (B) or of Tfm-only male mice (C) lack such nuclear AR staining, indicating that the HSA-AR trangene is not expressed in spinal motoneurons. Note that the nuclei of wt motoneurons are stained dark (arrow in A) as opposed to the motoneuronal nuclei of Tfm/Tg and Tfm-only male mice that are devoid of such AR immunoreactivity (arrows in B and C, respectively).

Scale bar = 30 microns.

Adult male mice of three different genotypes (wt, Tfm or Tfm/HSA-AR) were perfused with saline followed by 4% phosphate buffered paraformaldehyde. Tfm and Tfm/HSA-AR mice received s.c. injections of 500 μg of testosterone propionate dissolved in 0.05 ml sesame oil 1.5 – 2 hours prior to sacrifice to enhance detection of nuclear AR in spinal motoneurons as Tfm mice have extremely low levels of plasma T, well below normal wt levels (Jordan, unpublished observation). Spinal cords were harvested, postfixed for one hour in the same fixative and then stored overnight at 4 degrees C in 20% phosphate
Table 1. Male-limited perinatal lethality of HSA-AR transgene

<table>
<thead>
<tr>
<th>Genotype</th>
<th>L78 (n = 121)</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>No. at birth</td>
<td>% of total births</td>
<td>No. dead at birth</td>
<td>No. alive at weaning</td>
<td></td>
</tr>
<tr>
<td>Tg male</td>
<td>17*</td>
<td>14%</td>
<td>9</td>
<td>7*</td>
<td></td>
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<tr>
<td>WT male</td>
<td>39</td>
<td>32%</td>
<td>7</td>
<td>32</td>
<td></td>
</tr>
<tr>
<td>Tg female</td>
<td>35</td>
<td>29%</td>
<td>1</td>
<td>30</td>
<td></td>
</tr>
<tr>
<td>WT female</td>
<td>30</td>
<td>25%</td>
<td>7</td>
<td>23</td>
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</table>

<table>
<thead>
<tr>
<th>Genotype</th>
<th>L141 (n = 299)</th>
<th></th>
<th></th>
<th></th>
<th></th>
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</thead>
<tbody>
<tr>
<td></td>
<td>No. at birth</td>
<td>% of total births</td>
<td>No. dead at birth</td>
<td>No. alive at weaning</td>
<td></td>
</tr>
<tr>
<td>Tg male</td>
<td>46*</td>
<td>15%</td>
<td>36</td>
<td>3*</td>
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<tr>
<td>WT male</td>
<td>75</td>
<td>25%</td>
<td>11</td>
<td>64</td>
<td></td>
</tr>
<tr>
<td>Tg female</td>
<td>94</td>
<td>31%</td>
<td>16</td>
<td>76</td>
<td></td>
</tr>
<tr>
<td>WT female</td>
<td>84</td>
<td>28%</td>
<td>12</td>
<td>72</td>
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</tr>
</tbody>
</table>

Significant perinatal attrition is observed in HSA-AR Tg males but not females or in HSA-LacZ reporter mice (data not shown), suggesting that the lethality reflects an androgen-dependent function of overexpressed AR. Treatment of pregnant dams with the anti-androgen flutamide rescues some Tg males from death (data not shown), which also supports this view. *, significantly less than expected as indicated by $\chi^2$ statistic ($P < 0.05$).
Table 2. Motoneuron number and size is unaffected by the HSA-AR transgene despite profound motor deficits exhibited by line 141 Tg males

<table>
<thead>
<tr>
<th></th>
<th>L141 WT (n = 4)</th>
<th>L141 Tg (n = 3)</th>
<th>p-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of SNB motoneurons</td>
<td>66.3 ± 3.1</td>
<td>54.7 ± 3.8</td>
<td>n.s.</td>
</tr>
<tr>
<td>No. of DLN motoneurons</td>
<td>198 ± 16.6</td>
<td>180.3 ± 9.9</td>
<td>n.s.</td>
</tr>
<tr>
<td>No. of RDLN motoneurons</td>
<td>219.8 ± 17.5</td>
<td>204 ± 8.1</td>
<td>n.s.</td>
</tr>
<tr>
<td>SNB motoneuronal soma size, µm²</td>
<td>466.8 ± 26.5</td>
<td>533.8 ± 50</td>
<td>n.s.</td>
</tr>
<tr>
<td>DLN motoneuronal soma size, µm²</td>
<td>652 ± 23.4</td>
<td>633 ± 45.8</td>
<td>n.s.</td>
</tr>
<tr>
<td>RDLN motoneuronal soma size, µm²</td>
<td>387.2 ± 27.4</td>
<td>424.6 ± 38.4</td>
<td>n.s.</td>
</tr>
</tbody>
</table>

Formalin fixed spinal cords were sectioned through the lumbar enlargement at 30 µm on a freezing sliding microtome. Every section was collected, and missing sections were accounted for. All sections were Thionin stained for Nissl, and three separate motor neuron pools were quantified. Motoneuron number and soma size was measured in the spinal nucleus of the bulbocavernosus (SNB), the dorsolateral nucleus (DLN), and the retrodorsolateral nucleus (RDLN) using BioQuant Life Science software (version 8.00.20).