

Introduction

Polyglutamine (polyQ) diseases are caused by the expansion of a trinucleotide CAG repeat encoding glutamine in the causative genes and, to date, nine disorders have been identified as polyQ diseases [1]. Spinal and bulbar muscular atrophy (SBMA), also known as Kennedy's disease, was the first polyQ disease to be identified [2] and is characterized by premature muscular exhaustion, slow progressive muscular weakness, atrophy, and fasciculation in bulbar and limb muscles [3]. In SBMA, the pathogenic gene product is the androgen receptor (AR), which contains an abnormally expanded polyQ. The number of polymorphic CAG repeats in the *AR* gene is normally 14 to 32, but it is expanded to 40 to 62 CAGs in SBMA patients [4]. A correlation exists between the number of CAG repeats and disease severity [5]. The pathologic features of SBMA are motor neuron loss in the spinal cord and brainstem [3], and diffuse nuclear accumulations and nuclear inclusions (NIs) containing the mutant AR in the residual motor neurons and certain visceral organs [6].

Heat shock protein (Hsp) 90, one of the molecular chaperones, is essential for function and stability of the AR, the C-terminus of which has a high affinity for Hsp90, inducing the conformational change required for its nuclear translocation after ligand activation [7–9]. Hsp90 functions in a multi-component complex of chaperone proteins including Hsp70, Hop (Hsp70 and Hsp90 organizing protein), Cdc37, and p23. In addition, Hsp90 is involved in the folding, activation, and assembly of several proteins, known as Hsp90 client proteins [10]. As numerous oncoproteins belonging to the Hsp90 client protein family are selectively degraded in the ubiquitin–proteasome system (UPS) by Hsp90 inhibitors, 17-allylamino-17-demethoxygeldanamycin (17-AAG), a first-in-class Hsp90 inhibitor, is now under clinical trials as a novel molecular-targeted agent for a wide range of malignancies [11]. AR also belongs to the Hsp90 client protein family and is degraded in the presence of Hsp90 inhibitors [12–14].

In view of this ability of Hsp90 inhibitors to degrade Hsp90 client proteins, we have recently demonstrated that 17-AAG markedly ameliorated polyQ-mediated motor neuron degeneration through degradation of mutant AR [15]. This is apparently different from previous strategies employed against polyQ diseases, which unavoidably allowed abnormal protein to remain and placed much value mainly on the inhibition of protein aggregation. We consider that the ability to facilitate degradation of disease-causing protein by modulation of Hsp90 function would be of value when applied to SBMA and other related neurodegenerative diseases. In this paper, we review our research findings compared with previous studies and discuss the clinical application of Hsp90 inhibitors to neurodegenerative diseases.

Development of Hsp90 inhibitors

The most classical Hsp90 inhibitor is geldanamycin (GA), a natural product that was developed as an antifungal agent [16]. Later, GA was also found to have a potent and selective anti-tumor effect against a wide range of malignancies [17]. Although GA showed potential as a novel anti-cancer agent [18], this agent was also found to have intolerable liver toxicity [19]. To overcome this GA-induced liver toxicity, scientists at the US National Cancer Institute succeeded in developing a new derivative of GA, 17-AAG, that shares its important biological activities [20] but shows less toxicity [21]. Owing to this promising derivative 17-AAG, Hsp90 inhibitors have taken a major developmental leap in their clinical applications, and 17-AAG is now in phase clinical trials with encouraging results as an anti-cancer agent [22–26]. To generate more selective and less toxic derivatives than 17-AAG, further development of Hsp90 inhibitors is also being pursued [27–29].

The anti-tumor effect of Hsp90 inhibitors was previously thought to be due to the inhibition of tyrosine kinase [30]. The mechanism subsequently proved to be based on their ability to specifically bind to the Hsp90 ATP-binding site, thereby modulating Hsp90 function [31, 32] and proteasomal degradation of Hsp90 client proteins. As numerous oncoproteins were shown to belong to the family of Hsp90 client proteins [10], Hsp90 inhibitors are expected to become a new strategy in anti-tumor therapy [18]. Hsp90 inhibitors including GA and 17-AAG have been shown to have an advantageously higher selectivity for tumor cells compared with general anti-tumor agents [17]. Studies by Kamal et al. suggest a mechanism for this selectivity; Hsp90 in tumor cells is more likely to be incorporated in the Hsp90 multi-chaperone complex than the Hsp90 in normal cells is, thereby increasing their binding affinity to 17-AAG by more than 100-fold [33, 34].

We thought that this selectivity of Hsp90 inhibitors would also be advantageous for the treatment of neurodegenerative diseases. However, as neurodegenerative diseases generally follow a chronic progression and the medical treatment is long compared with that for malignancy, the toxic side effects of the treatments would need to be extensively suppressed. Therefore, we decided to explore the possibility of using 17-AAG as a therapeutic agent for neurodegenerative diseases by examining its effects on mutant AR in cultured cells and in a mouse model of SBMA.

A model mouse of SBMA and a potent hormonal therapy

We had previously generated transgenic mice expressing the full-length human AR containing either 24 or 97 CAG repeats under the control of a cytomegalovirus enhancer and a chicken actin promoter [35]. The mice with 97 CAG repeats (AR-97Q) exhibited progressive motor impairment, while none of those with 24 CAG repeats (AR-24Q) showed abnormal phenotypes [35]. Other laboratories have

also generated various animal models of SBMA, almost all of which display phenotypic expressions of motor dysfunction [36]. For researching a truly effective molecular-targeted therapy, it is imperative to do so in a model that approximates the native state and metabolism of the disease-causing protein *in vivo*. We therefore consider that our SBMA mice carrying full-length AR are more beneficial for investigating therapeutic agents than those carrying the truncated one. Our transgenic mice indeed have a very severe phenotype, which is different to some extent from the human form of the disease, but they demonstrate polyQ-induced motor neuron degeneration and provide a beneficial tool to screen therapeutic agents to rescue this condition as we previously described [37]. For further details about the clinical features and our mouse model of SBMA, please refer to Katsuno et al. [38, 39].

We have already experimentally demonstrated several therapeutic approaches using this model [35, 37, 40, 41] and consequently confirmed that leuprorelin, a luteinizing hormone-releasing hormone agonist that reduces testosterone release from the testis, significantly rescued motor dysfunction and nuclear accumulation of mutant AR in our SBMA mice. Due to its minimal invasiveness established in human and its powerful efficacy demonstrated in the above model [37], this hormonal therapy has already been in human clinical trials with encouraging results [42]. However, it is an extremely specialized therapy for SBMA and cannot be applied to other polyQ diseases [35, 37, 38]. In contrast to this hormonal therapy, 17-AAG would be a potential therapeutic agent for SBMA as well as for other related diseases [15].

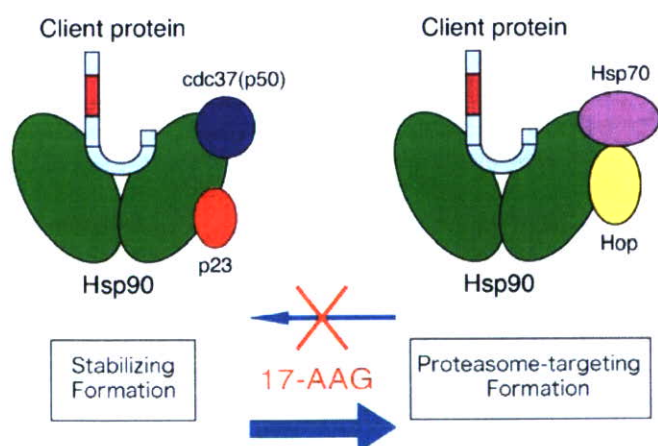


Fig. 1 Hsp90-inhibitor-induced change in Hsp90 complex. Hsp90 inhibitor (17-AAG) specifically binds ATP-binding site of Hsp90, resulting in a shift of the Hsp90 complex. To exert its effects on client proteins, Hsp90 functions in a multi-component complex of co-chaperone proteins including Hsp70, Hop, Cdc37, and p23. Two main forms of this complex exist. One complex is a proteasome-targeting form associated with Hsp70 and Hop, and the other is a stabilizing form with Cdc37 and p23. Hsp90 inhibitors block the progression of the Hsp90 complex toward the stabilizing form and shift it to the proteasomal-targeting form. This figure is modified from a model proposed by Neckers [14]

17-AAG alters the form of the Hsp90 complex, leading to proteasomal degradation of mutant AR

Hsp90 functions in a multi-component complex of chaperone proteins, including Hsp70, Hop, Cdc37, and p23, leading to the folding, activation, and assembly of Hsp90 client proteins [10]. In addition, the Hsp90 complexes are thought to exist in two main forms: one complex is a proteasome-targeting form associated with Hsp70 and Hop, and the other is a stabilizing form with Cdc37 and p23 [14, 43–45] (Fig. 1). Hop is known to independently bind to both Hsp90 and Hsp70, which promotes the Hsp90/Hsp70 linkage, and is thought to direct the triage decision for client proteins by bridging the Hsp90–Hsp70 interaction [45]. On the other hand, p23 is thought to modulate Hsp90 activity in the last stages of the chaperoning pathway, leading to the stabilization of Hsp90 client proteins in an ATP-dependent manner [46]. Hsp90 inhibitors, including 17-AAG, inhibit the ATP-dependent progression of the Hsp90 complex toward the stabilizing form and shift it to the proteasomal-targeting form, resulting in proteasomal degradation of the Hsp90 client protein [47, 48]. Steroid receptors, including the progesterone receptor and the glucocorticoid receptor, were the first Hsp90 client proteins to be identified [49, 50]. As for AR, Hsp90 is essential to maintain its high ligand-binding affinity and its stabilization [7, 12]. In practice, Hsp90 inhibitors reduce androgen ligand-binding affinity and induce the degradation of AR [12, 13].

To address the question of whether 17-AAG also promotes the degradation of the disease-causing protein of SBMA, polyQ-expanded mutant AR, we treated SH-SY5Y cells highly expressing the wild-type (AR-24Q) or mutant (AR-97Q) AR for 6 h with 36 μ M 17-AAG or with dimethyl sulfoxide (DMSO) as control, in the absence or presence of the proteasome inhibitor, MG132. Immunoblot analysis demonstrated that the monomeric mutant AR decreased significantly more than the wild type did, suggesting that the mutant AR is more sensitive to 17-AAG than the wild type is. The degradation of wild-type and mutant AR by 17-AAG was completely blocked by the proteasome inhibitor, MG132 (Fig. 2a), suggesting that 17-AAG-facilitated degradation was dependent on the proteasome system as previously reported [47, 48].

Next, we examined changes in the Hsp90 chaperone complex in wild-type and mutant AR-expressing cultured cells after 17-AAG treatments. Immunoprecipitation with anti-AR antibody revealed that Hsp90-chaperone-complex-associated Hop was markedly increased, and p23 decreased in a 17-AAG dose-dependent manner, suggesting that 17-AAG resulted in the shifting of the AR-Hsp90 chaperone complex from a mature stabilizing form with p23 to a proteasome-targeting form with Hop. This chaperone complex shift appears to be very rapid as has been suggested previously [50, 51]. The loss of p23 from the mutant AR-Hsp90 complex was significantly greater than that from the wild-type one (Fig. 2b). Furthermore, these studies also strongly suggested that the mutant AR is more prone to be in the multi-chaperone complexes of

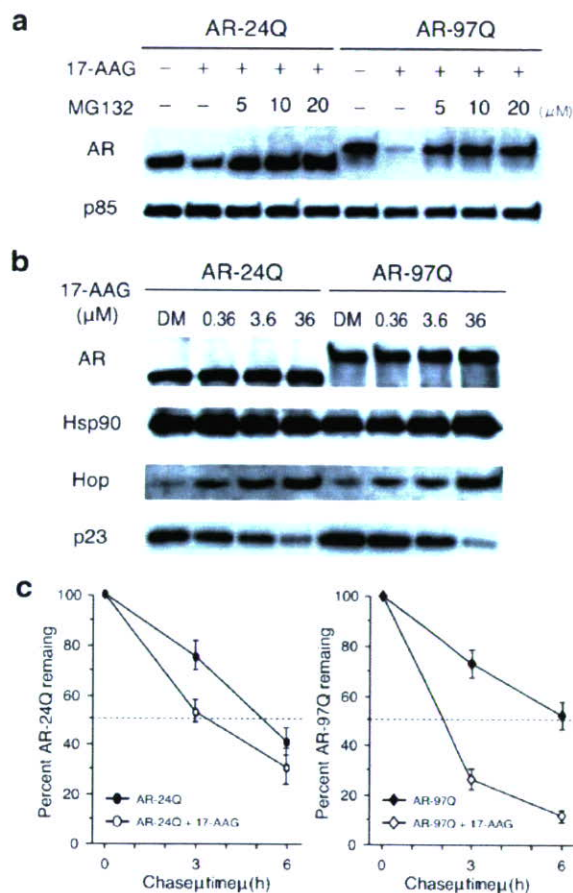


Fig. 2 a–c 17-AAG-induced changes in the AR–Hsp90 complex: correlation to proteasomal degradation. **a** 17-AAG treatment (36 μ M, 6 h) of transfected SHSY5Y cells reduced the levels of mutant AR (AR-97Q) significantly more than the wild-type AR (AR-24Q); however, both decreases were completely blocked by the proteasomal inhibitor, MG132. **b** Immunoblots of lysates from transfected cells treated for 30 min with 17-AAG and immunoprecipitated with AR-specific antibody. The short time exposure to 17-AAG did not decrease the amount of mutant AR, but there were dose-dependent changes in both Hop and p23. There were no changes in the amounts of Hsp90 complexed with mutant AR. There were no changes in the expression of Hop, p23, and Hsp90 in whole lysates in the presence of 17-AAG (data not shown) **c** The effects of 17-AAG on the half-life of wild-type and mutant AR assessed from pulse-chase experiments. The amounts of AR-24Q remaining in the absence and presence of 17-AAG are indicated by closed circles (●) and open circles (○), respectively. The amounts of AR-97Q remaining in the absence and presence of 17-AAG are indicated by closed (◆) and open (◇) diamonds, respectively. Mutant AR was degraded more rapidly than the wild-type AR in the presence of 17-AAG. Values are expressed as means \pm SE ($n=4$)

Hsp90 with p23, which eventually enhances 17-AAG-dependent proteasomal degradation of mutant AR.

To determine whether the decrease in AR was due to protein degradation or to changes in RNA expression, the turnover of wild-type and mutant AR were then assessed with a pulse-chase labeling assay. In the presence of 17-AAG, the mutant AR and the wild-type AR had half-lives of 2 h and 3.5 h, respectively (Fig. 2c), while the mRNA levels for both the wild-type and mutant AR were quite similar [15]. These data indicate that 17-AAG preferentially degrades the mutant AR protein without altering

mRNA levels. These in vitro studies indicated that the mutant AR was a good target protein of 17-AAG. To determine if it would also be preferentially degraded in vivo, we next examined the effects of 17-AAG in SBMA transgenic mice.

17-AAG ameliorates the phenotype in a mouse model of SBMA mouse without detectable toxicity

We administered 17-AAG at doses of 2.5 or 25 mg/kg to males of the transgenic mouse model carrying full-length human AR with either 24Q or 97Q. The disease progression of AR-97Q mice treated with 25 mg/kg 17-AAG (Tg-25) was significantly ameliorated, and that of mice treated with the 2.5 mg/kg 17-AAG (Tg-2.5) was also mildly ameliorated (Fig. 3a). The AR-97Q mice treated with vehicle only (Tg-0) showed motor impairment assessed by the Rotarod task as early as 9 weeks after birth while the Tg-25 mice showed initial impairment only 18 weeks after birth and with less deterioration than the Tg-0 mice ($P<0.005$; Fig. 3a). Tg-2.5 mice showed intermediate levels of impairment in Rotarod performance (Fig. 3a). 17-AAG also significantly prolonged the survival rate of the Tg-2.5 and Tg-25 mice compared with the Tg-0 mice ($P=0.004$ and $P<0.001$, respectively; Fig. 3a). No lines were distinguishable in terms of body weight at birth; however, by 16 weeks, the Tg-0 mice showed obvious differences in body size, muscular atrophy, and kyphosis compared with the Tg-25 mice (Fig. 3b).

When mouse tissues were immunohistochemically stained for mutant AR using the IC2 antibody, which specifically recognizes expanded polyQ, quantitative analysis revealed marked reductions in IC2-positive nuclear accumulation in the spinal motor neurons and muscles of the Tg-25 mice compared with those of the Tg-0 mice (Fig. 3c).

Western blot analysis from lysates of the spinal cord and muscle of AR-97Q mice revealed high molecular weight mutant AR protein complex retained in the stacking gel as well as a band of monomeric mutant AR, whereas only the band of wild-type monomeric AR was visible in tissue from the AR-24Q mice (Fig. 3d). 17-AAG treatments significantly diminished both the high molecular weight complex and the monomer of mutant AR in the spinal cord and muscle of the AR-97Q mice but only slightly diminished the wild-type monomeric AR in AR-24Q mice (Fig. 3d). 17-AAG treatments decreased the amount of monomeric AR in AR-97Q mice by 64.4% in the spinal cord and 45.0% in the skeletal muscle, but only 25.9 and 12.5%, respectively, in AR-24Q mice (Fig. 3d). Thus, the reduction rate of the monomeric mutant AR was significantly higher than that of the wild-type AR in both spinal cord and skeletal muscle ($P<0.001$ and $P<0.01$ respectively). The levels of wild-type and mutant AR mRNA were similar in the respective mice treated with 17-AAG [15]. These observations indicate that 17-AAG markedly reduces not only the high molecular weight

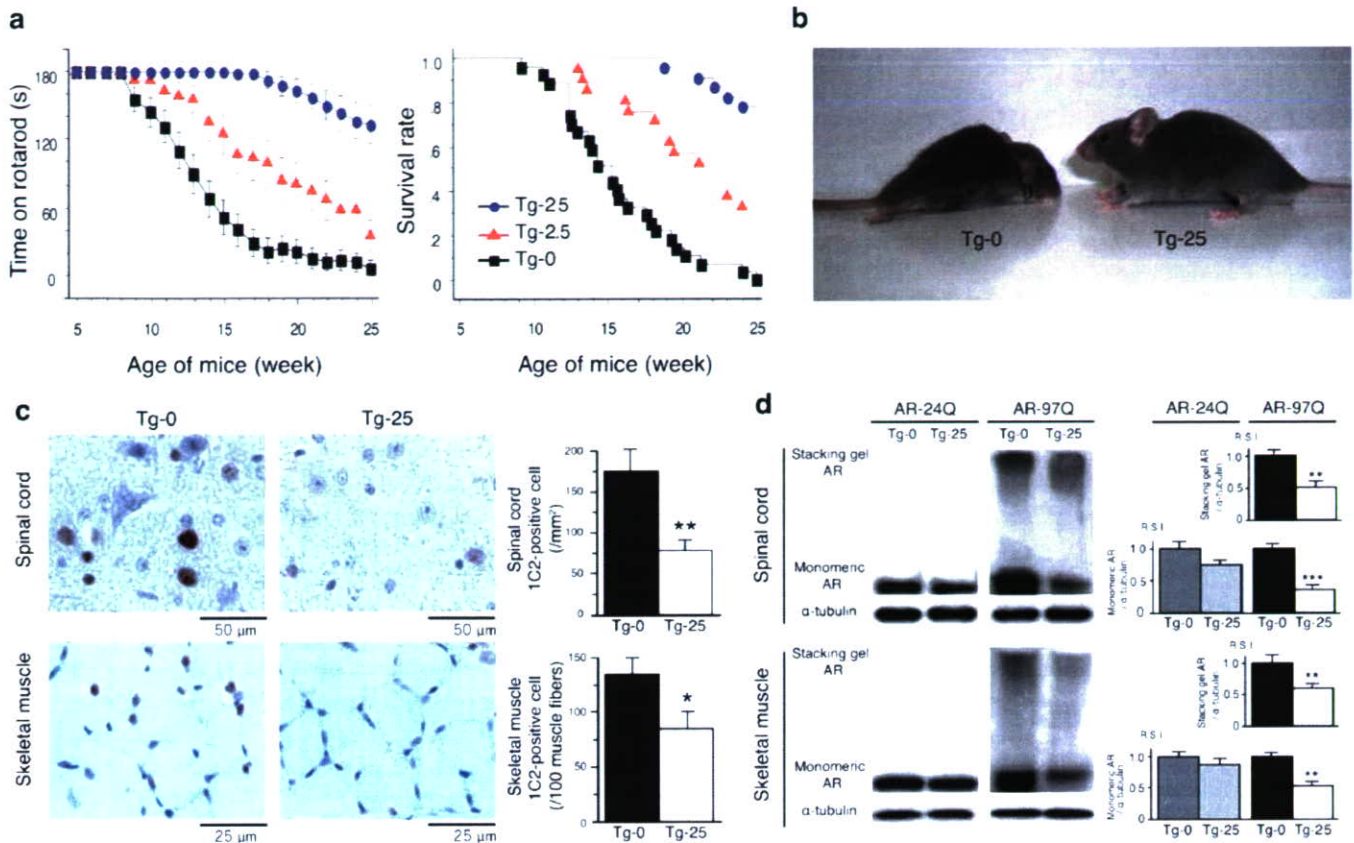


Fig. 3 a–d Effects of 17-AAG on transgenic SBMA mice. **a** Tg-0, Tg-2.5, and Tg-25 represent AR-97Q mice treated with vehicle alone and 2.5 and 25 mg/kg 17-AAG, respectively (each group, $n=27$). The Tg-25 remained longer on the Rotarod than the Tg-0 mice did. A Kaplan–Meier plot shows the prolonged survival of Tg-2.5 and Tg-25 mice compared with the Tg-0 mice, which were all dead by 25 weeks of age ($P=0.004$, $P<0.001$, respectively). 17-AAG was less effective at the dose of 2.5 than 25 mg/kg in all parameters tested. **b** Representative photographs of a 16-week-old Tg-0 mouse (left) reveal an obvious difference in size and illustrate muscular atrophy and kyphosis compared with an age-matched Tg-25 mouse (right). **c** Immunohistochemical staining with 1C2 antibody showed marked differences in diffuse nuclear staining and nuclear inclusions between DMSO-treated mice (Tg-0) and 17-AAG-treated (Tg-25) mice in the spinal anterior horn and skeletal muscle, respectively. There was a significant reduction in 1C2-positive cell staining in the spinal cord (** $P<0.01$) and skeletal muscle (* $P<0.05$) in the Tg-25 compared with the Tg-0. Values are expressed as means \pm SE ($n=6$).

d Western blot analysis of tissue from AR-24Q and AR-97Q mice probed with an AR-specific antibody. In both spinal cord and muscle of mice treated with 17-AAG, there was a significant decrease in the amount of complexed, mutant AR in the stacking gel and monomeric mutant AR in AR-97Q mice, but only slightly less monomeric wild-type AR in AR-24Q mice compared with that from their respective, untreated control mice. Results of a densitometric analysis demonstrated that the 17-AAG-induced reduction of monomeric mutant AR was significantly greater than that of the wild-type monomeric AR. 17-AAG resulted in a 64.4% decline in monomeric mutant AR in the spinal cord and a 45.0% decline in the skeletal muscle, whereas, there was only a 25.9% decline in the spinal cord and a 12.5% decline in the skeletal muscle of AR-24Q mice. These results show significant differences in the reduction rate between wild-type and mutant AR in both spinal cord and skeletal muscle. Values are expressed as means \pm SE ($n=5$). Statistical differences are indicated by asterisks (* $P<0.05$; ** $P<0.01$; *** $P<0.001$)

mutant AR complex but also the monomeric mutant AR protein by preferential degradation of mutant AR.

17-AAG facilitates the degradation of monomeric mutant AR, reducing its aggregation; a therapeutic approach that directly targets the disease-causing protein

In both cultured cells and transgenic SBMA mice, we have demonstrated both the efficacy and safety of 17-AAG [15]. Among the other proposed therapeutic approaches we have previously examined [35, 37, 40, 41], the efficacy of 17-AAG most closely approximated the very successful hormonal therapy using the LH-RH analog, leuprorelin

[15]. But, unlike leuprorelin, the Hsp90 inhibitor 17-AAG holds enormous potential for application to a wide-range of neurodegenerative diseases in addition to SBMA as previously reported [52–54]. For development of Hsp90 inhibitor treatment in neurological disorders, we regard this general versatility as very important.

In neurodegenerative diseases, recent studies have shown that disease-causing proteins in the process of aggregating have more toxic consequences than they do in either the nascent state or when in NI [55]. NIs have been thought to be a beneficial coping response to toxic mutant protein [56]. We have accumulated several pieces of data demonstrating that 17-AAG is capable of reducing aggregated protein in animal models of SBMA [15]. In both Western blot and filter trap analyses in AR-97Q

models, 17-AAG significantly diminished the insoluble high molecular weight complex of mutant AR as well as the soluble monomer. Moreover, in an immunostaining study of nervous tissue in AR-97Q mice, 17-AAG also significantly reduced diffuse nuclear staining. In SBMA patients, the extent of diffuse nuclear accumulation of mutant AR in motor and sensory neurons of the spinal cord was closely related to CAG repeat length [6]. We consider that 17-AAG had a curative effect on SBMA mice by reducing these toxic proteins as well as the soluble monomeric form.

It is difficult to determine whether 17-AAG facilitates the degradation of, specifically, these toxic intermediate proteins, as 17-AAG has the potent ability to also degrade their precursors (i.e., the monomers). One possible mode of 17-AAG action is that it may inhibit the aggregation of mutant AR via Hsp70 and Hsp40 induction. The pharmacological induction of Hsp70 and Hsp40 using Hsp90 inhibitors has already been shown to inhibit polyQ-induced abnormal aggregation of the huntingtin protein [57]. However, as 17-AAG displayed only a limited ability to induce Hsp70 and Hsp40 in mouse tissue [15], we think that the large decrease in AR seen in the insoluble fraction *in vivo*, rather than being a result of HSP induction, may be

due to 17-AAG's potent ability to degrade the soluble monomeric form of mutant protein, thereby preventing aggregation in the first place. There is no doubt that a reduction of the main culprit protein must have curative properties against various neurodegenerative diseases. In fact, one therapeutic approach that directly reduced abnormal protein using RNA interference has already proved beneficial in various mouse models of polyQ diseases and amyotrophic lateral sclerosis [58–60].

Hsp70 is also known to accelerate proteasome-dependent degradation of polyQ abnormal protein [40, 61]. However, in our hands, mutant AR was markedly decreased after 17-AAG treatment even when Hsp70 and Hsp40 induction was completely blocked in the presence of a protein synthesis inhibitor [15], strongly suggesting that 17-AAG contributes to the preferential degradation of mutant AR mainly through Hsp90 chaperone complex formation and subsequent proteasome-dependent degradation rather than via Hsp70 and Hsp40 induction. Therefore, we think that, to reap the most therapeutic benefits, Hsp90 inhibitors should be applied against neurodegenerative diseases in which the causative protein is, like AR, an Hsp90 client protein.

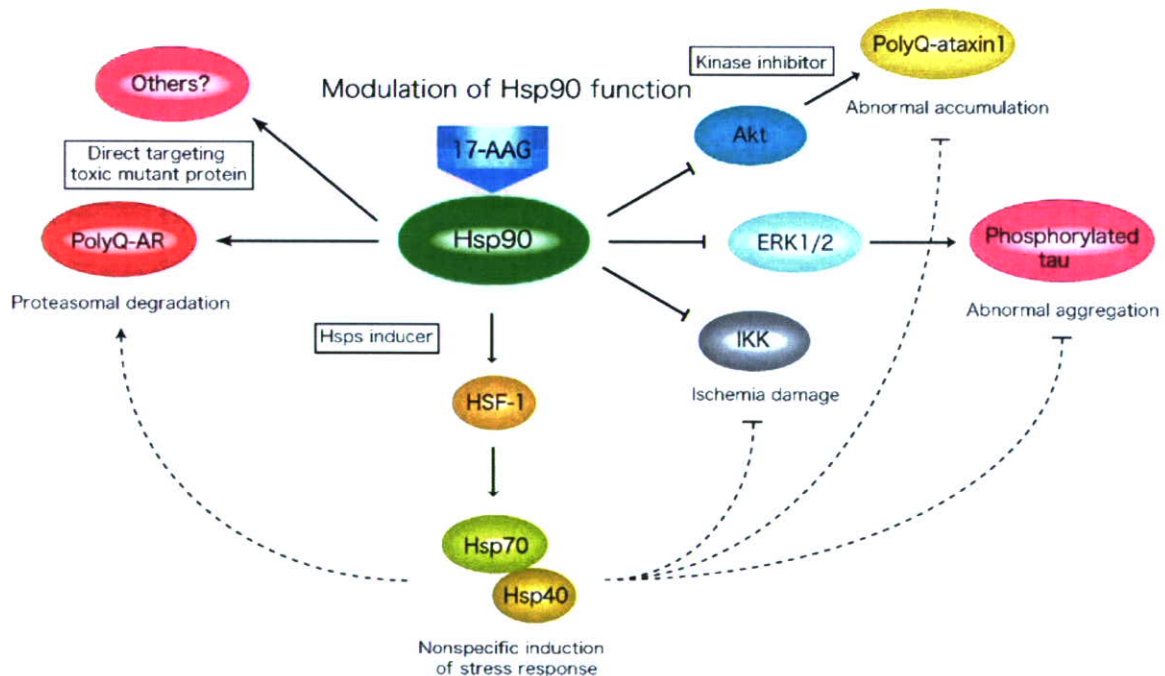


Fig. 4 Clinical application of Hsp90 inhibitors in neurological disorders. 17-AAG specifically binds to the Hsp90 ATP-binding site and disrupts its ATP-dependent function, resulting in inactivation and degradation of Hsp90 client proteins. Therapeutic approaches using Hsp90 inhibitors have now emerged that are unrelated to their role in inducing HSPs. In SBMA, where it may have its most effective potential, 17-AAG directly accelerates proteasomal degradation of the disease-causing protein, polyQ-expanded AR. However, it is still unclear whether other neurodegenerative disease-causing proteins are also Hsp90 client proteins. Many kinases involved in signal transduction do belong to the family of

Hsp90 client proteins targeted by 17-AAG. ERK is associated with stabilizing phosphorylated tau. 17-AAG reduces the total amount of phosphorylated tau and its abnormal aggregation by inhibiting ERK activation. Following this same mechanism, 17-AAG might also reduce the abnormal accumulation of ataxin-1 by inhibiting Akt activation or alleviate cerebral infarction by inhibiting IKK activation, which is also an Hsp90 client protein, as well as by inducing HSPs. Hsp90 inhibitors are known to nonspecifically induce HSPs, although this effect was quite limited in our mouse model of SBMA. The induction of HSPs by Hsp90 inhibitors seems to play a supplementary role in neurodegenerative disorders

17-AAG functions with preserved UPS function

As we demonstrated in an *in vitro* study, 17-AAG-induced degradation requires a well-preserved proteasome function [15]. However, a question concerning the usefulness of this pharmacological approach to facilitate a self-clearing system has been raised [62]. It is generally accepted that the ubiquitin–proteasome system (UPS) is strongly involved in the pathology of polyQ diseases, as many components of the ubiquitin–proteasome and molecular chaperones are known to co-localize with polyQ-containing NIs [63, 64]. Previous reports of studies performed in cultured cell models suggested that an impairment of the UPS is probably a common pathology in polyQ diseases [65–67]. If this hypothesis were true, 17-AAG could not exert its pharmacological effect on polyQ diseases; its therapeutic effects are dependent on a preserved proteasome function [15, 47, 48, 62].

In this regard, recent studies using *in vivo* proteasome assays have raised serious questions concerning the impaired UPS hypothesis of polyQ diseases [68–70]. It has been reported that neuronal dysfunction developed without significant impairment of the UPS in a mouse model of SCA7 [69]. Consistent with this, it was also demonstrated that proteasome impairment did not contribute to pathogenesis in a mouse model of Huntington's disease (HD) [70]. Furthermore, in conditional mouse models of polyQ disease, genetic loss of the abnormal gene product led to a rapid clearance of pre-existing polyQ-mediated NIs and reversible improvement of the abnormal phenotypes [71, 72]. If the UPS were irreversibly damaged in polyQ diseases, then pre-existing NIs could not be diminished.

While it remains unclear what the difference is in proteasome function in *in vitro* and *in vivo* models, our research in a mouse model of SBMA indicates that impairment of the UPS is not a major etiology, at least in *in vivo* models of polyQ diseases. We therefore consider that treatment with 17-AAG, which takes advantage of a self-clearing system to target disease-causing proteins, is a reasonable therapeutic strategy against polyQ-related and other neurodegenerative diseases.

The expected beneficial effects of 17-AAG against other neurodegenerative diseases

Among neurodegenerative-disease-causing proteins, only AR in SBMA is established as an Hsp90 client protein at this time. It will be interesting to assess whether other neurodegenerative-disease-causing proteins also belong to the family of Hsp90 client proteins. Recent studies have already revealed that some Hsp90 client proteins exerted adverse influences on several neurological disorders [73–75], indicating that the clinical application of Hsp90 inhibitors could expand beyond the treatment of oncological diseases. With reference to previous reports, we now discuss the possibility that 17-AAG could be applicable to neurodegeneration other than SBMA (Fig. 4).

Using 17-AAG as an inducer of HSPs

Hsp90 inhibitors are known to possess the unique pharmacological effect of inducing a stress response and, in addition to their use as anti-cancer agents, have also been developed as pharmacological HSP inducers [52, 76]. This pharmacological effect has already been confirmed in human clinical trials [22]. Murakami et al. were the first to show that the Hsp90 inhibitor herbimycin had the ability to induce Hsp70 in various cultured cell models [77]. Thereafter, Hsp90 proved to be a repressor of heat transcription factor (HSF-1) [78]. Hsp90 inhibitors cause a disassociation of HSF-1 from the Hsp90 complex and a trimerization of HSF-1, thereby resulting in HSP activation. Based on the ability to induce HSPs, Hsp90 inhibitors have also been applied to non-oncological diseases [52].

A great number of reports revealed that forced overexpression of Hsp70 resulted in acquisition of tolerance against various types of stresses and protection against apoptosis in various disease models [79]. In a wide range of polyQ disease models, both genetic and pharmacological overexpression of HSPs has been shown to suppress aggregate formation and cellular toxicity [63, 80, 81]. There is no doubt that HSP induction is beneficial for various neurodegenerative diseases [54]. We have also demonstrated that both genetic and pharmacological overexpression of Hsp70 significantly ameliorated expression of the abnormal phenotype in a transgenic mouse model of SBMA [40, 82].

Taking advantage of HSP induction, many studies have already showed that Hsp90 inhibitors exerted potential neuroprotective effects in: a model of HD [57, 83, 84], tauopathies [28, 85–87], Parkinson's disease [88–90], stroke [91, 92], and autoimmune encephalomyelitis [93]. In addition, Hsp90 inhibitors themselves have been shown to have some neuroprotective effects against various stresses, such as drug-induced toxicity, oxidative stress, and oxygen-glucose deprivation [94–97]. As for polyQ diseases, Sittler et al. [57] first showed that GA significantly suppressed aggregation of mutant huntingtin in a cultured cell model of HD via induction of the Hsp70 and Hsp40 heat shock response. Thus, the enhancement of cellular defenses using Hsp90 inhibitors is a very reasonable clinical application for neurodegenerative diseases.

In polyQ diseases, Bates and his colleagues [83] showed a progressive decrease in the expression of Hsp70 and Hsp40 in a mouse model of HD, which was also observed in our SBMA model [82]. The ability of Hsp90 inhibitors to significantly induce HSPs has been demonstrated only in cultured cell models and in the fly model, but not in mammals. Therefore, further investigation should be performed to address how much Hsp90 inhibitors can induce HSPs in mouse models of neurodegenerative disorders other than SBMA. Although it appears to be obvious that it would be advantageous for the treatment of neurodegeneration, in inducing HSPs by Hsp90 inhibitors, in view of our research finding in *in vivo* models, it would be unadvisable to rely only on the induction of nonspecific HSPs for human clinical trials.

Using 17-AAG as a kinase inhibitor in neurodegeneration

Phosphorylated tau is a representative disease-causing protein associated with tauopathies including fronto-temporal dementia, progressive supranuclear palsy, corticobasal degeneration, and multiple system atrophy. It is interesting to note that phosphorylated tau is a targeted protein of Hsp90 inhibitors [28, 85, 86]. Dou et al. recently showed that GA and 17-AAG indirectly blocked abnormal tau phosphorylation by inhibition of the Raf–MEK–extracellular signal-regulated kinase (ERK) pathway [98], of which upstream kinase Raf is also an Hsp90 client protein [10, 99]. ERK is known to mediate the activation and stabilization of phosphorylated tau [100, 101]. Along these same lines, LaFevre-Bernt and Ellerby [102] demonstrated that polyQ-expanded, mutant-AR-mediated neuronal cell death by ERK activation and that selective inhibition of the ERK pathway reduced polyQ-induced cell death. Based on this mechanism of inhibiting ERK activation, 17-AAG might also ameliorate abnormal phenotypic expression in the mouse model of SBMA. Furthermore, in other neurodegenerative disorders, evidence has accumulated suggesting that ERK activation is an important executor of neuronal damage [103–106]. Hsp90 inhibitors are well known to have the ability to inhibit various kinase activity [10]. This pharmacological effect of Hsp90 inhibitors, to reduce abnormal kinase activity, could be applied to neurodegenerative diseases as well as oncological diseases and could have far-reaching influence on the clinical application of Hsp90 inhibitors.

Zoghbi and colleagues demonstrated that Akt/PI3K was essential for stabilization and accumulation of mutant ataxin-1 in the polyQ-associated disease SCA1 [73, 107]. Akt is also an Hsp90 client protein, whose activity is significantly reduced by Hsp90 inhibition [108, 109]. Thus, reduction of Akt kinases activity by Hsp90 inhibition might be a therapeutic approach for SCA1. Although Akt/PI3K is believed to be a major pathway mediating survival signals in neuronal cells [110], their finding raises an issue about this hypothesis.

Hsp90 inhibitors have been found to have some neuroprotective effects such as on axonal regeneration in cultured cell models [94, 111]. Koprivica et al. demonstrated that epidermal growth factor receptor (EGFR) activation mediates inhibition of axon regeneration [74]. That EGFR is also an Hsp90 client protein [112, 113] might help explain how Hsp90 inhibition is related to axonal regeneration. In another example, GA markedly attenuates ischemic brain damage [91, 92] and I κ B kinase (IKK), an Hsp90 client protein [114], plays an important role in ischemia-induced neuronal death [75, 115], suggesting that GA may ameliorate ischemia brain damage by reducing IKK activity as well as by inducing HSPs.

There is a caveat to this suggestion, however. If 17-AAG is to be applied clinically to treat neurodegenerative diseases with the expectation of reducing abnormal kinase activity, we should also keep in mind the possibility that 17-AAG might also inhibit some kinase activation that

exerts cytoprotective effects against neuron degeneration. Taking HD as an example, the efficacy of GA has already been shown based on its ability to induce HSPs [57, 83]. However, a report recently released by Apostol et al. showed that ERK1/2 activation protects against mutant huntingtin-induced toxicity [116]. Furthermore, in a cultured cell model of HD carrying full-length huntingtin, various kinase activities were inhibited by mutant polyQ-expanded huntingtin, but not by normal huntingtin [117, 118]. If ERK activation plays a major role in protecting against HD phenotype expression, there is concern that 17-AAG might exert an adverse effect on HD by inhibiting ERK activation. Before applying 17-AAG to a neurological disorder, we should assess whether the kinase targeted by Hsp90 inhibitor is a true exacerbating factor for the pathology. While there may be some debate over whether 17-AAG should be used as a kinase inhibitor in neurodegeneration, if the application of 17-AAG is suitably performed, this agent would be expected to effectively inhibit abnormal kinase activity in several neurological disorders, possibly leading to cures for these diseases. Hence, this strategy is also of value to extend the versatility of Hsp90 inhibitors as therapeutic agents for neurological disorders.

Conclusion

When considering a role for molecular chaperones in neurological disorders, it should be said that Hsp70 and Hsp40 have received most of the attention, especially in neurodegenerative diseases, as these chaperones have the desirable ability to refold abnormal proteins or to carry them to degradation as a part of the system of protein quality control [54, 119]. Compared with this, Hsp90 is not known to directly fold non-native proteins but rather to bind to substrate proteins only at a late stage of folding [120]. Considering our research findings and those of the other above-mentioned reports, in addition to its role in malignancies, Hsp90 exerts an adverse influence on the nervous system in some situations. In this case, it is reasonable to consider modulating Hsp90 function appropriately.

The ability of 17-AAG to facilitate the degradation of abnormal toxic protein through the modulation of Hsp90 function would be directly applicable to SBMA and probably other neurodegenerative disorders as well. But we should keep in mind that 17-AAG is not a panacea for neurological disorders because it has only limited ability to induce Hsp70 and Hsp40 *in vivo*. 17-AAG is expected to exert the most effective therapeutic potential against diseases in which the main etiological factor is mediated by Hsp90 client proteins, like AR in SBMA. We believe that more research should be invested in examining the effects of Hsp90 inhibitors on neurodegeneration and that suitably modulating Hsp90 function has great potential to become a new molecular-targeted therapy against a wide range of neurodegenerative diseases.

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Review

Pathogenesis, animal models and therapeutics in Spinal and bulbar muscular atrophy (SBMA)

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Abstract

Spinal and bulbar muscular atrophy (SBMA) is a hereditary neurodegenerative disease characterized by slowly progressive muscle weakness and atrophy of bulbar, facial, and limb muscles. The cause of SBMA is expansion of a trinucleotide CAG repeat, which encodes the polyglutamine tract, in the first exon of the androgen receptor (AR) gene. SBMA chiefly occurs in adult males, whereas neurological symptoms are rarely detected in females having mutant AR gene. The cardinal histopathological finding of SBMA is loss of lower motor neurons in the anterior horn of spinal cord as well as in brainstem motor nuclei. Animal models carrying human mutant AR gene recapitulate polyglutamine-mediated motor neuron degeneration, providing clues to the pathogenesis of SBMA. There is increasing evidence that testosterone, the ligand of AR, plays a pivotal role in the pathogenesis of neurodegeneration in SBMA. The striking success of androgen deprivation therapy in SBMA mouse models has been translated into clinical trials. In addition, elucidation of pathophysiology using animal models leads to emergence of candidate drugs to treat this devastating disease: HSP inducer, Hsp90 inhibitor, and histone deacetylase inhibitor. Utilizing biomarkers such as scrotal skin biopsy would improve efficacy of clinical trials to verify the results from animal studies. Advances in basic and clinical researches on SBMA are now paving the way for clinical application of potential therapeutics.

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Keywords: Spinal and bulbar muscular atrophy; Polyglutamine; Androgen receptor; Testosterone; Luteinizing hormone-releasing hormone analog; Heat shock protein; Geranylgeranylacetone; 17-Allylamino geldanamycin; Histone deacetylase inhibitor; Axonal transport

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History and nomenclature

More than a hundred years have elapsed since the first description of spinal and bulbar muscular atrophy (SBMA) from Hiroshi Kawahara, who described the clinical and hereditary characteristics of two Japanese brothers with progressive bulbar palsy (Kawahara, 1897). This work was followed by several reports on similar cases with or without X-linked pattern of inheritance (Katsuno et al., 2004). SBMA is also known as Kennedy disease (KD), named after William R. Kennedy, whose study on 11 patients from 2 families depicted the clinical, genetical, and pathological features of this disorder (Kennedy et al., 1968). Other names for this disease are bulbospinal neuronopathy and bulbospinal muscular atrophy.

In 1991, the cause of SBMA was identified as the expansion of a trinucleotide CAG repeat in the androgen receptor (AR) gene (La Spada et al., 1991). This was the first discovery of polyglutamine-mediated neurodegenerative diseases, and subsequent studies using transgenic animal models opened the door to development of pathogenesis-based therapies for this devastating disease.

Clinical features

SBMA exclusively affects adult males. The prevalence of this disease is estimated to be 1–2 per 100,000, whereas a considerable number of patients may have been misdiagnosed as other neuromuscular diseases including amyotrophic lateral sclerosis (Fischbeck, 1997). Patients of various ethnic backgrounds have been reported around the world.

Major symptoms of SBMA are weakness, atrophy, and fasciculations of bulbar, facial and limb muscles (Sperfeld et al., 2002; Katsuno et al., 2004). In extremities, involvement is usually predominant in proximal musculature. The onset of weakness is usually between 30 and 60 years but is often preceded by nonspecific symptoms such as postural tremor and muscle cramps. Although fasciculations in the extremities are rarely present at rest, they are easily induced when patients hold their arms horizontally or bend their legs while lying on their backs. These contraction fasciculations are especially noticeable in the face, neck, and tongue and are usually present in the early stage. Fatigability after exercise might also be accompanied. Bilateral facial and masseter muscle weakness, poor uvula and soft palatal movements, and atrophy of the tongue with fasciculations are often encountered. Speech has a nasal quality in most cases due to reduced velopharyngeal closure. Advanced cases often develop dysphagia, eventually resulting in aspiration or choking. Muscle tone is usually hypotonic, and no pyramidal signs are detected. Deep tendon reflex is diminished or absent with no pathological reflex. Sensory involvement is largely restricted to vibration sense which is affected distally in the legs. Cerebellar symptoms, dysautonomia, and cognitive impairment are absent. Patients occasionally demonstrate signs of androgen insensitivity such as gynecomastia, testicular atrophy, dyserection, and decreased fertility, some of which are detected before the onset of motor symptoms. Abdominal obesity is common, whereas male pattern baldness is rare in patients with SBMA.

Electromyogram shows neurogenic abnormalities, and distal motor latencies are often prolonged in nerve conduction study. Both sensory nerve action potential and sensory evoked potential are reduced or absent. Endocrinological examinations frequently reveal partial androgen resistance with elevated serum testosterone level. Serum creatine kinase level is elevated in the majority of patients. Hyperlipidemia, liver dysfunction, and glucose intolerance are also detected in some patients. Profound facial fasciculations, bulbar signs, gynecomastia, and sensory disturbance are the main clinical features distinguishing SBMA from other motor neuron diseases, although gene analysis is indispensable for diagnosis. Female patients are usually asymptomatic, but some express subclinical phenotypes including high amplitude motor unit potentials on electromyography (Sobue et al., 1993).

The progression of SBMA is usually slow, but a considerable number of patients need assistance to walk in their fifties or sixties. Life-threatening respiratory tract infection often occurs in the advanced stage of the disease, resulting in early death in some patients. No specific therapy for SBMA has been established. Testosterone has been used in some patients, although it has no effects on the progression of SBMA.

Etiology

The cause of SBMA is expansion of a trinucleotide CAG repeat, which encodes the polyglutamine tract, in the first exon of the androgen receptor (AR) gene (La Spada et al., 1991). The CAG repeat within AR ranges in size from 9 to 36 in normal subjects but from 38 to 62 in SBMA patients. Expanded polyglutamine tracts have been found to cause several neurodegenerative diseases including SBMA, Huntington's disease, several forms of spinocerebellar ataxia, and dentatorubral-pallidolusian atrophy (Gatchel and Zoghbi, 2005). These disorders, known as polyglutamine diseases, share salient clinical features including anticipation and somatic mosaicism, as well as selective neuronal and nonneuronal involvement despite widespread expression of the mutant gene. There is an inverse correlation between the CAG repeat size and the age at onset or the disease severity adjusted by the age at examination in SBMA as documented in other polyglutamine diseases (Doyu et al., 1992). These observations explicitly suggest that common mechanisms underlie the pathogenesis of polyglutamine diseases.

AR, the causative protein of SBMA, is an 110-kDa nuclear receptor which belongs to the steroid/thyroid hormone receptor family (Poletti, 2004). AR mediates the effects of androgens, testosterone, and dihydrotestosterone, through binding to an androgen response element in the target gene to regulate its expression. AR is essential for major androgen effects including normal male sexual differentiation and pubertal sexual development, although AR-independent nongenomic function of androgen has been reported. AR is expressed not only in primary and secondary sexual organs but also in nonreproductive organs including the kidney, skeletal muscle, adrenal gland, skin, and nervous system, suggesting its far-reaching influence on a variety of mammalian tissues. In the central nervous system, the expression level of AR is relatively high in spinal and brainstem

motor neurons, the same cells which are vulnerable in SBMA. The AR gene is located on chromosome Xq11–12. This 90-kb DNA contains eight exons coding for the functional domains specific to the nuclear receptor family. The first exon codes for the N-terminal transactivating domain. Exons 2 and 3 code for the DNA-binding domain, whereas exons 4 through 8 code for the ligand-binding domain. The N-terminal transactivating domain, in which a CAG trinucleotide repeat locates, possesses a major transactivation function maintained by interaction with general transcriptional coactivators such as c-AMP response element binding protein-binding protein (CBP), TAFIII30, and steroid receptor coactivator-1 (SRC-1). The CAG repeat beginning at codon 58 in the first exon of AR encodes polyglutamine tract. The length of this repeat is highly variable because of the slippage of DNA polymerase upon DNA replication. Whereas its abnormal elongation causes SBMA, the shorter CAG repeat is likely to increase the risk of prostate cancer (Clark et al., 2003). Transcriptional coactivators also possess glutamine-rich regions modulating protein–protein interaction with the N-terminal transactivating domain of AR.

The expansion of a polyglutamine tract in AR has been implicated in the pathogenesis of SBMA in two different, but not mutually exclusive, ways: loss of normal AR function induces neuronal degeneration; and the pathogenic AR acquires toxic property damaging motor neurons. Since AR possesses trophic effects on neuronal cells, one can assume that loss of AR function may play a role in the pathogenesis of SBMA. Expansion of the polyglutamine tract mildly suppresses the transcriptional activities of AR, probably because it disrupts interaction between the N-terminal transactivating domain of AR and transcriptional coactivators (Poletti, 2004). Although this loss of function of AR may contribute to the androgen insensitivity in SBMA, the pivotal cause of neurodegeneration in SBMA has been believed to be a gain of toxic function of the pathogenic AR due to expansion of the polyglutamine tract.

This hypothesis is supported by the observation that motor impairment has never been observed in severe testicular feminization (Tfm) patients lacking AR function or in AR knockout mice. Moreover, a transgenic mouse model carrying an elongated CAG repeat driven by human AR promoter demonstrated motor impairment, suggesting that the expanded polyglutamine tract is sufficient to induce the pathogenic process of SBMA (Adachi et al., 2001).

Aggregation of abnormal protein has been considered to be central to the pathogenesis of neurodegenerative diseases such as Alzheimer disease, Parkinson disease, amyotrophic lateral sclerosis, and prion disease. An expanded polyglutamine stretch alters conformation of causative proteins, resulting in aggregation of the proteins. It is now widely accepted that aggregation of these abnormal proteins in neurons is the primary event in the pathogenesis of polyglutamine diseases. The rate-limiting step of aggregation has been proposed to be the formation of oligomeric nucleus, which may occur form after a repeat length-dependent conformational change of polyglutamine monomer from a random coil to a parallel, helical β -sheet (Wyttenbach, 2004). Several experimental observations indicate that formation of toxic oligomers, or intermediates, of abnormal polyglutamine-containing protein instigates a series of cellular events which lead to neurodegeneration (Muchowski and Wacker, 2005). This hypothesis is likely to be the case in SBMA.

Pathology

Histopathological studies provide important information on the pathogenesis of polyglutamine-mediated neurodegeneration. The fundamental histopathological finding of SBMA is loss of lower motor neurons in the anterior horn of spinal cord as well as in brainstem motor nuclei except for the third, fourth and sixth cranial nerves (Fig. 1A) (Sobue et al., 1989). The

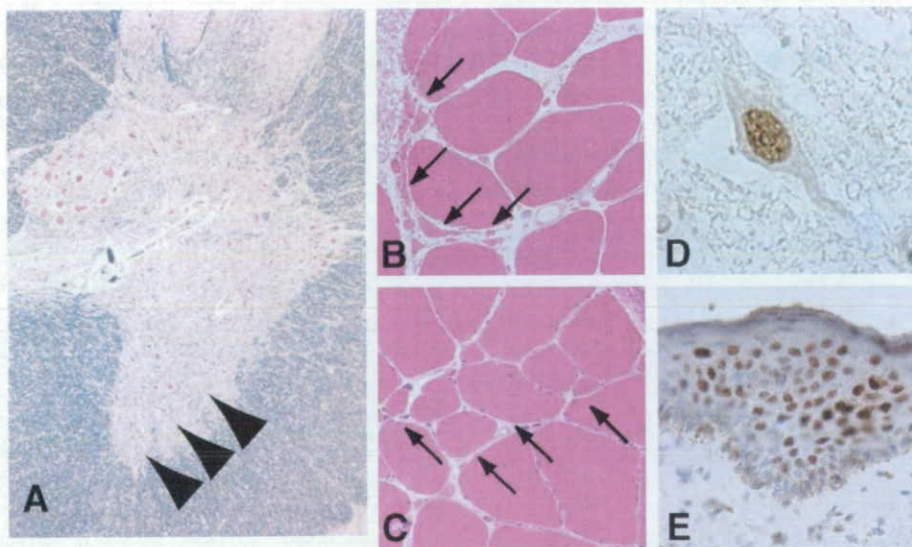


Fig. 1. Histopathology of SBMA. (A) A transverse section of spinal cord demonstrates marked depletion of motor neurons in the anterior horn. (B and C) HE staining of skeletal muscle shows both neurogenic (B, arrows) and myogenic changes (C, arrows). (D) A residual motor neuron in the lumbar anterior horn shows a diffuse nuclear accumulation of pathogenic androgen receptor detected by anti-polyglutamine antibody. (E) Nuclear accumulation of pathogenic AR is also detected in nonneuronal tissues such as scrotal skin (E).

number of nerve fibers is reduced in the ventral spinal nerve root, reflecting motor neuronopathy. Sensory neurons in the dorsal root ganglia were less severely affected, and large myelinated fibers demonstrate a distally accentuated sensory axonopathy in the peripheral nervous system. Neurons in the Onufrowicz nuclei, intermediolateral columns, and Clarke's columns of the spinal cord are generally well preserved. Muscle histopathology includes both neurogenic and myogenic findings: there are groups of atrophic fibers with a number of small angular fibers, fiber type grouping and clumps of pyknotic nuclei as well as variability in fiber size, hypertrophic fibers, scattered basophilic regenerating fibers, and central nuclei (Figs. 1B and C).

A pathologic hallmark of polyglutamine diseases is the presence of nuclear inclusions (NIs). In SBMA, NIs containing the pathogenic AR are found in the residual motor neurons in the brainstem and spinal cord as well as in nonneuronal tissues including prostate, testis, and skin (Li et al., 1998). These inclusions are detectable using antibodies recognizing a small portion of the N-terminus of the AR protein, but not by those against the C-terminus of the protein. This observation implies that the C-terminus of AR is truncated or masked upon formation of NI. A full-length AR protein with expanded polyglutamine tract is cleaved by caspase-3, liberating a polyglutamine-containing toxic fragment, and the susceptibility to cleavage is polyglutamine repeat length-dependent (Kobayashi et al., 1998). Thus, proteolytic cleavage is likely to enhance the toxicity of the pathogenic AR protein. Electron microscopic immunohistochemistry shows dense aggregates of AR-positive granular material without limiting membrane, both in the neural and nonneural inclusions, in contrast to the other polyglutamine diseases in which NIs take the form of filamentous structures. Although NI is a disease-specific histopathological finding, its role in pathogenesis has been heavily debated. Several studies have suggested that NI may indicate cellular response coping with the toxicity of abnormal polyglutamine protein (Arrasate et al., 2004). Instead, the diffuse nuclear accumulation of the mutant protein has been considered essential for inducing neurodegeneration in polyglutamine diseases including SBMA.

An immunohistochemical study on autopsied SBMA patients using an anti-polyglutamine antibody demonstrates that diffuse nuclear accumulation of the pathogenic AR is more frequently observed than NIs in the anterior horn of spinal cord (Adachi et al., 2005). Intriguingly, the frequency of diffuse nuclear accumulation of the pathogenic AR in spinal motor neurons strongly correlates with the length of the CAG repeat in the AR gene. No such correlation has been found between NI occurrence and the CAG repeat length. Similar findings have also been reported on other polyglutamine diseases. Taken together, it appears that the pathogenic AR containing an elongated polyglutamine tract principally accumulates within the nuclei of motor neurons in a diffusible form, leading to neuronal dysfunction and eventual cell death. In support of this hypothesis, neuronal dysfunction is halted by genetic modulation preventing nuclear import of the pathogenic polyglutamine-containing protein in cellular and animal models of polyglutamine diseases (Gatchel and Zoghbi, 2005).

Since human AR is widely expressed in various organs, nuclear accumulation of the pathogenic AR protein is detected not only in the central nervous system but also in nonneuronal tissues such as scrotal skin (Figs. 1D and E). The degree of pathogenic AR accumulation in scrotal skin epithelial cells tends to be correlated with that in the spinal motor neurons in autopsy specimens, and it is well correlated with CAG repeat length and inversely correlated with the motor functional scale (Banno et al., *in press*). These findings indicate that scrotal skin biopsy with anti-polyglutamine immunostaining is a potent biomarker with which to monitor SBMA pathogenic processes. Since SBMA is a slowly progressive disorder, appropriate biomarkers would help improve the power and cost effectiveness of longitudinal clinical treatment trials.

Molecular pathogenesis and therapeutic strategies

Ligand-dependent pathogenesis in animal models of SBMA

SBMA is unique among polyglutamine diseases in that the pathogenic protein, AR, has a specific ligand, testosterone, which alters the subcellular localization of the protein by favoring its nuclear uptake. AR is normally confined to a multi-heteromeric inactive complex in the cell cytoplasm and translocates into the nucleus in a ligand-dependent manner. This ligand-dependent intracellular trafficking of AR appears to play important roles in the pathogenesis of SBMA.

In order to investigate ligand effect in SBMA, we generated transgenic mice expressing the full-length human AR containing 24 or 97 CAGs under the control of a cytomegalovirus enhancer and a chicken β -actin promoter (Katsuno et al., 2002). This model recapitulated not only the neurologic disorder but also the phenotypic difference with gender which is a specific feature of SBMA. The mice with 97CAGs (AR-97Q) exhibited progressive motor impairment, although those with 24 CAGs did not show any manifested phenotypes. Affected AR-97Q mice demonstrated small body size, short life span, progressive muscle atrophy, and weakness as well as reduced cage activity, all of which were markedly pronounced and accelerated in the male AR-97Q mice, but either not observed or far less severe in the female AR-97Q mice. The onset of motor impairment detected by the rotarod task was at 8 to 9 weeks of age in the male AR-97Q mice while 16 weeks or more in the females. The 50% mortality ranged from 66 to 132 days of age in the male AR-97Q mice, whereas mortality of the female AR-97Q mice remained only 10 to 30% at more than 210 days. Western blot analysis revealed the transgenic AR protein smearing from the top of the gel in the spinal cord, cerebrum, heart, muscle, and pancreas. Although the male AR-97Q mice had more smearing protein than their female counterparts, the female AR-97Q mice had more monomeric AR protein. The nuclear fraction contained the most of smearing pathogenic AR protein. Diffuse nuclear staining and less frequent NIs detected by 1C2, an antibody specifically recognizing the expanded polyglutamine tract, were demonstrated in the neurons of spinal cord, cerebrum, cerebellum, brainstem, and dorsal root ganglia as well as in nonneuronal tissues such as heart, muscle, and

pancreas. Male AR-97Q mice showed markedly more abundant diffuse nuclear staining and NIs than females, in agreement with the symptomatic and Western blot profile differences with gender. Despite the profound sexual difference of the pathogenic AR protein expression, there was no significant difference in the expression of the transgene mRNA between the male and female AR-97Q mice. These observations indicate that the testosterone level plays important roles in the sexual difference of phenotypes, especially in the post-transcriptional stage of the pathogenic AR.

The dramatic sexual difference of phenotypes led us to hormonal interventions in our mouse model. First, we castrated male AR-97Q mice in order to decrease their testosterone level. Castrated male AR-97Q mice showed profound improvement of symptoms, histopathologic findings, and nuclear localization of the pathogenic AR compared with the sham-operated male AR-97Q mice. Body weight, motor function, and lifespan of male AR-97Q mice were significantly improved by castration. Western blot analysis and histopathology revealed diminished nuclear accumulation of the pathogenic AR in the castrated male AR-97Q mice. Next, we administered testosterone to the female AR-97Q mice. In contrast to castration of the male mice, testosterone caused significant aggravation of symptoms, histopathologic features, and nuclear localization of the pathogenic AR in the female AR-97Q mice. Since the nuclear translocation of AR is ligand-dependent, testosterone appears to show toxic effects in the female AR-97Q mice by accelerating nuclear translocation of the pathogenic AR. On the contrary, castration prevented the nuclear localization of the pathogenic AR by reducing the testosterone level. The nuclear accumulation of the pathogenic AR protein with an expanded polyglutamine tract is likely essential in inducing neuronal cell dysfunction and degeneration in the majority of polyglutamine diseases. It thus appears logical that reduction in testosterone level improves phenotypic expression by preventing nuclear localization of the pathogenic AR. In support of this hypothesis, the ligand-dependent neurodegeneration has also been revealed in a fruit fly model of SBMA (Takeyama et al., 2002). Alternatively, castration may enhance protective effects of molecular chaperones, which are normally associated with AR and dissociate upon ligand binding.

Testosterone blockade therapy for SBMA

Successful treatment of AR-97Q mice with castration inspired us testosterone blockade therapies using leuporelin and flutamide (Katsuno et al., 2003). Leuporelin is a potent luteinizing hormone-releasing hormone (LHRH) analog suppressing the releases of gonadotrophins, luteinizing hormone and follicle-stimulating hormone. This drug has been used for a variety of sex hormone-dependent diseases including prostate cancer, endometriosis, and prepuberty. The primary pharmacological target of leuporelin is the anterior pituitary. Through its agonizing effect on LHRH-releasing cells, it initially promotes the releases of gonadotrophins, resulting in transient increase in the serum level of testosterone or estrogens. After this surge, the continued use of this drug induces desensitization of the

pituitary by reducing LHRH receptor binding sites and/or uncoupling of receptors from intracellular processes. Within about 2 to 4 weeks of leuporelin administration, human serum testosterone level decreases to the extent achieved by surgical castration. The effects are maintained during the treatment, suggesting that continuous administration of leuporelin is required for its clinical use. This drug thus has been provided as sustained release depot taking the form of polymer microspheres. On the other hand, flutamide, the first discovered androgen antagonist, has highly specific affinity for AR and competes with testosterone for binding to the receptor. It has been used for the treatment of prostate cancer, usually in association with an LHRH analog, in order to block the action of adrenal testosterone. Although flutamide suppresses the androgen-dependent transactivation, it does not reduce the plasma levels of testosterone.

Leuporelin successfully inhibited nuclear accumulation of the pathogenic AR, resulting in marked amelioration of neuromuscular phenotypes seen in the male AR-97Q mice (Fig. 2). Leuporelin initially increased the serum testosterone level by agonizing the LHRH receptor but subsequently reduced it to undetectable levels. Androgen blockade effects were also confirmed by reduced weights of the prostate and seminal vesicle. The leuporelin-treated AR-97Q mice showed longer lifespan, larger body size, and better motor performance compared with vehicle-treated mice. Although leuporelin-induced infertility was prevented by dose reduction, the therapeutic effects on neuromuscular phenotypes were insufficient at a lower dose of leuporelin. In the Western blot analysis and anti-polyglutamine immunohistochemistry, the leuporelin-treated male AR-97Q mice demonstrated a markedly diminished amount of the pathogenic AR in the nucleus, suggesting that leuporelin successfully reduced nuclear AR accumulation. Testosterone, which was given from 13 weeks of age, markedly aggravated neurological symptoms and pathologic findings of leuporelin-treated male AR-97Q mice. Leuporelin appears to improve neuronal dysfunction by preventing ligand-dependent nuclear translocation of the pathogenic AR in the same way as castration. Given its minimal invasiveness and established safety, leuporelin appears to be a promising therapeutic agent for SBMA. In a preliminary open trial, 6-month treatment with leuporelin significantly diminished nuclear accumulation of pathogenic AR in the scrotal skin of patients, suggesting that androgen deprivation intervenes in the pathogenic process of human SBMA, as demonstrated in animal studies (Banno et al., *in press*). Another trial on a larger scale is currently underway to verify clinical benefits of leuporelin for SBMA patients.

Leuporelin-treated AR-97Q mice showed deterioration of body weight and rotarod task at the age of 8–9 weeks, when serum testosterone initially increased through the agonistic effect of leuporelin. This change was transient and followed by sustained amelioration along with consequent suppression of testosterone production. The foot print analysis also revealed temporary exacerbation of motor impairment. Immunostaining of tail specimen, sampled from the same individual mouse, demonstrated an increase in the number of the muscle fibers with nuclear 1C2 staining at 4 weeks of leuporelin administration,

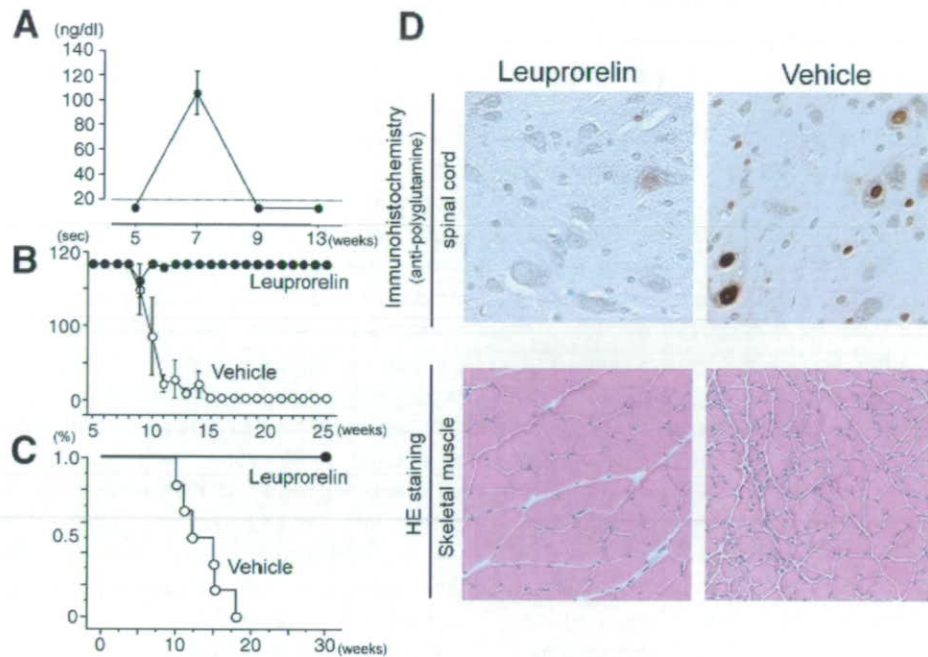


Fig. 2. Effects of leuporelin on mutant androgen receptor (AR) expression and neuropathology of male AR-97Q mice. (A) Serum testosterone level in AR-97Q mice. Leuporelin initially increased serum testosterone level but subsequently reduced it to undetectable levels. (B and C) Rotarod task (B) and survival rate (C) of the AR-97Q mice. Leuporelin markedly improved motor function of the mice at the dose. (D) Immunohistochemistry using 1C2 showed marked differences in diffuse nuclear staining and nuclear inclusions between the leuporelin-treated and vehicle-treated AR-97Q male mice in the spinal anterior horn. HE staining of the muscle in the vehicle-treated male mouse revealed apparent grouped atrophy and small angulated fibers, which were not seen in the leuporelin-treated mice.

although this 1C2 staining was diminished by another 4 weeks of treatment. Our results indicate that preventing nuclear translocation of the pathogenic AR is enough to reverse both symptomatic and pathologic phenotypes in our AR-97Q mice. In support with these observations, testosterone deprivation by means of castration reverses motor dysfunction in another transgenic mouse model of SBMA showing fairly slow progression (Chevalier-Larsen et al., 2004). Since the pathophysiology of AR-97Q mice is neuronal dysfunction without neuronal cell loss, our results indicate that the pathogenesis of polyglutamine diseases is reversible at least in its initial stage. From therapeutic point of view, it is of importance to determine the early dysfunctional period in the natural history of human SBMA.

By contrast, flutamide, AR antagonist, did not ameliorate symptoms, pathologic features, or nuclear localization of the pathogenic AR in the male AR-97Q mice, although there was no significant difference in the androgen blockade effects between flutamide and leuporelin. Flutamide does not inhibit, but may even facilitate, the nuclear translocation of AR. In consistency with mouse study, this AR antagonist also promotes nuclear translocation of the pathogenic AR containing an expanded polyglutamine in cellular and fly models of SBMA (Takeyama et al., 2002; Walcott and Merry, 2002). This appears to be the reason why flutamide demonstrated no therapeutic effect in our transgenic mouse model of SBMA. Flutamide is not likely to be a proper therapeutic agent for SBMA.

The castrated or leuporelin-treated AR-97Q mice showed phenotypes similar to those seen in the female AR-97Q mice, implying that motor impairment of SBMA patients can be reduced to the level in females. SBMA has been considered an

X-linked disease, whereas other polyglutamine diseases show autosomal dominant inheritance. In fact, SBMA female patients hardly manifest clinical phenotypes, although they possess similar number of a CAG repeat in the disease allele of AR gene as their siblings with SBMA (Sobue et al., 1993; Mariotti et al., 2000). Reduction in the mutant AR expression due to X-inactivation may prevent females from disease manifestation, but hormonal intervention studies using mouse and fly models clearly suggest that low level of testosterone prevents nuclear accumulation of the pathogenic AR protein, resulting in a lack of neurological phenotypes in the females. This view is strongly supported by the observation that manifestation of symptoms is minimal even in homozygous females of SBMA (Schmidt et al., 2002). Therefore, it seems inappropriate to regard SBMA as an X-recessive inherited disease, but rather its neurological phenotype is likely to depend on testosterone concentration.

Role of heat shock proteins in pathogenesis of SBMA

Many components of ubiquitin-proteasome and molecular chaperones are known to colocalize with polyglutamine-containing NIs, implying that failure of cellular defense mechanism underlies neurodegeneration in polyglutamine diseases. Heat shock protein (HSP), a stress-inducible molecular chaperone, is another key to elucidation of the pathogenesis of SBMA. HSPs are classified into different families according to molecular size: Hsp100, Hsp90, Hsp70, Hsp60, Hsp40, and small HSPs (Macario and Conway de Macario, 2005). These HSPs are either constitutively expressed or inducibly synthesized after cellular stress. HSPs play a crucial role in maintaining correct folding, assembly, and intracellular transport of proteins.

For example, Hsp70 and Hsp90, essential components of AR-chaperone complex in the cell cytoplasm, regulate function, nuclear translocation, and degradation of AR (Heinlein and Chang, 2001). Under toxic conditions, HSP synthesis is rapidly upregulated, and nonnative proteins are refolded as a consequence. Therefore, HSPs have attracted a great deal attention as cytoprotective agents against detrimental conditions including ischemia and malignancy.

Several studies suggest that polyglutamine elongation interferes with the protective cellular responses against cytotoxic stress (Wytenbach, 2004). Truncated AR with an expanded polyglutamine tract delays the induction of Hsp70 after heat shock (Cowan et al., 2003). The threshold of HSP induction is known to be relatively high in spinal motor neurons (Batulan et al., 2003). Expression levels of HSPs are decreased in the brain lesion of an animal model of HD and in that of the SBMA mouse (Hay et al., 2004; Katsuno et al., 2005). Taken together, impairment of HSP induction capability is implicated in the pathogenesis of motor neuron degeneration in SBMA. Not only are HSPs implicated in the pathogenesis of neurodegeneration, but they are also potent suppressors of polyglutamine toxicity. There is increasing evidence that HSPs abrogate polyglutamine-mediated cytotoxicity by refolding and solubilizing the pathogenic proteins (Wytenbach, 2004; Muchowski and Wacker, 2005). Hsp70 cooperates with Hsp40 in functioning as a molecular chaperone. These HSPs are proposed to prevent the initial conformation conversion of abnormal polyglutamine-containing protein from a random coil to a β -sheet, leading to attenuation of toxic oligomer formation (Wytenbach, 2004). Overexpression of Hsp70, together with Hsp40, inhibits toxic accumulation of abnormal polyglutamine-containing protein and suppresses cell death in a variety of cellular models of polyglutamine diseases including SBMA (Kobayashi et al., 2000). Hsp70 has also been shown to facilitate proteasomal degradation of abnormal AR protein in a cell culture model of SBMA (Bailey et al., 2002). The favorable effects of Hsp70 have been verified in studies using mouse models of polyglutamine diseases. Overexpression of the inducible form of human Hsp70 markedly ameliorated symptomatic and histopathological phenotypes of our transgenic mouse model of SBMA (Adachi et al., 2003). These beneficial effects are dependent on Hsp70 gene dosage and correlate with the reduction in the amount of nuclear-localized AR protein. It should be noted that the soluble form of the pathogenic AR was also significantly decreased in amount by Hsp70 overexpression, suggesting the degradation of the pathogenic AR may have been accelerated by overexpression of this molecular chaperone.

Favorable effects obtained by genetic modulation of HSP suggest that pharmacological induction of molecular chaperones might be a promising approach to SBMA and other polyglutamine diseases. Geranylgeranylacetone (GGA), an acyclic isoprenoid compound with a retinoid skeleton, has been shown to strongly induce HSP expression in various tissues (Hirakawa et al., 1996). Oral administration of GGA upregulates the levels of Hsp70, Hsp90, and Hsp105 via activation of heat shock factor-1 in the central nervous system

and inhibits nuclear accumulation of the pathogenic AR protein, resulting in amelioration of polyglutamine-dependent neuromuscular phenotypes of SBMA transgenic mice (Katsuno et al., 2005). Given its extremely low toxicity, this compound has been used as an oral anti-ulcer drug. Although a high dose appears to be needed for clinical effects, GGA appears to be a safe and promising therapeutic candidate for polyglutamine-mediated neurodegenerative diseases including SBMA.

Inhibition of Hsp90 is also demonstrated to arrest the neurodegeneration in SBMA mouse (Waza et al., 2005). Hsp90 functions in a multi-chaperone complex, assisting proper folding, stabilization, and assembly of so-called client proteins including various oncoproteins and AR (Pratt and Toft, 2003). The Hsp90-client protein complex is stabilized when it is associated with p23, a cochaperone interacting with Hsp90. Treatment with 17-allylamino geldanamycin (17-AAG), a potent Hsp90 inhibitor, dissociated p23 from the Hsp90-AR complex, and thus facilitated proteasomal degradation of the pathogenic AR in cellular and mouse models of SBMA. 17-AAG thereby inhibits nuclear accumulation of this protein, leading to marked amelioration of motor phenotypes of the SBMA mouse model without detectable toxicity (Fig. 3). Of interest is the finding that the pathogenic AR is preferentially targeted to proteasomal degradation in the presence of 17-AAG compared with wild-type AR. Given a high association between p23 and the AR containing expanded polyglutamine, it appears logical that the pathogenic AR is more dependent on Hsp90 to maintain folding and function than wild-type AR and thus is particularly susceptible to Hsp90 inhibition. 17-AAG is also capable of inducing Hsp70 in cellular and mouse models of SBMA. Collectively, 17-AAG, which is now under clinical trials for a wide range of malignancies, would be a good candidate for treatment of SBMA.

Transcriptional dysregulation in SBMA

Disruption of transcriptional machinery has also been hypothesized to underlie the pathogenesis of polyglutamine diseases (Sugars and Rubinsztein, 2003). Gene expression analysis indicates that transcriptional disruption is an early change in the pathogenesis of mouse models of polyglutamine diseases. Transcriptional coactivators such as CBP are sequestered into the polyglutamine-containing NIs through protein–protein interaction in mouse models and patients with polyQ diseases (Nucifora et al., 2001). Alternatively, the interaction between transcriptional coactivators and soluble pathogenic protein has also been demonstrated in animal models of polyglutamine diseases as well as in postmortem tissues of patients (Steffan et al., 2001). The expression of genes regulated through CBP-mediated transcription is decreased in mouse models of polyglutamine diseases (Sugars and Rubinsztein, 2003). CBP functions as histone acetyltransferase, regulating gene transcription and chromatin structure. It has been indicated that the histone acetyltransferase activity of CBP is suppressed in cellular models of polyglutamine diseases. Taken together, transcriptional dysregulation due to decrease in histone acetylation is likely to underlie the pathogenesis of neurodegeneration in polyglutamine diseases. This hypothesis is exemplified by our experimental

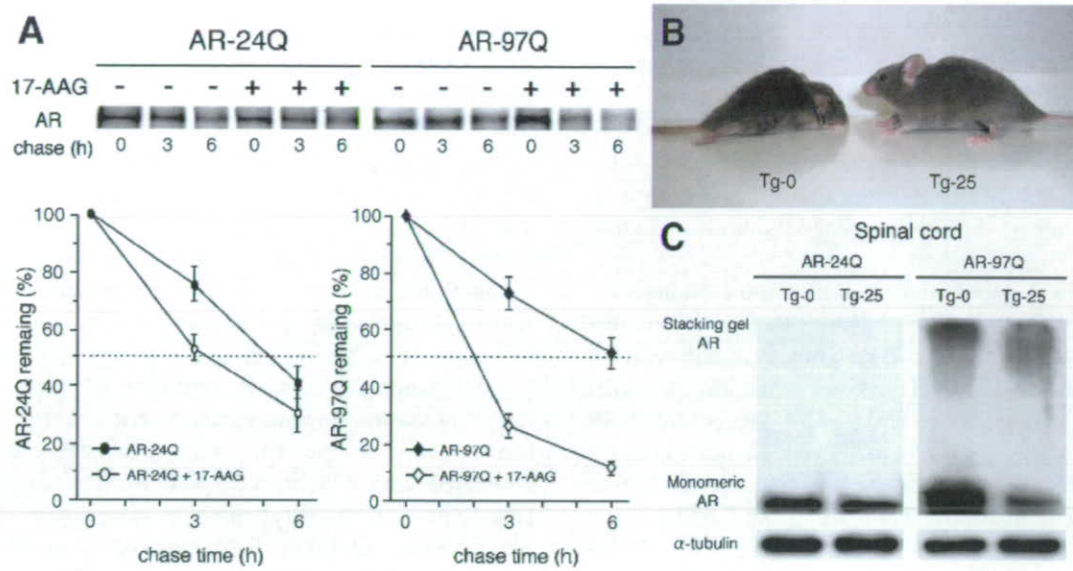


Fig. 3. Effects of 17-AAG on mutant androgen receptor (AR) turnover. (A) Pulse-chase analysis of two forms of AR. The pathogenic AR containing prolonged polyglutamine is degraded more rapidly than the wild-type AR in the presence of 17-AAG. (B) Muscle wasting is obvious in a vehicle-treated SBMA mouse (Tg-0), whereas it is hardly detected in an age-matched SBMA mouse treated with 25 mg/kg of 17-AAG (Tg-25). (C) Western blot analysis of total homogenates from the spinal cord of transgenic mice probed with an anti-AR antibody. 17-AAG decreases the amount of AR in mice bearing the pathogenic AR (AR-97Q), but this effect is only slightly observed in those expressing wild-type AR (AR-24Q).

observation that acetylation of nuclear histone H3 is significantly diminished in SBMA mice (Minamiyama et al., 2004). Additionally, dysfunction of CBP results in a decreased expression of vascular endothelial growth factor in another mouse model of SBMA, indicating the transcriptional alteration is a trigger of neurodegeneration in this disease (Sopher et al., 2004).

Histone acetylation level is determined by interplay between histone acetyltransferase and histone deacetylase (HDAC). Recruitment of HDAC to target genes represses transcription, leading to aberrant cellular function. Since cancellation of HDAC activity results in augmentation of histone acetylation and subsequent restoration of gene transcription, HDAC

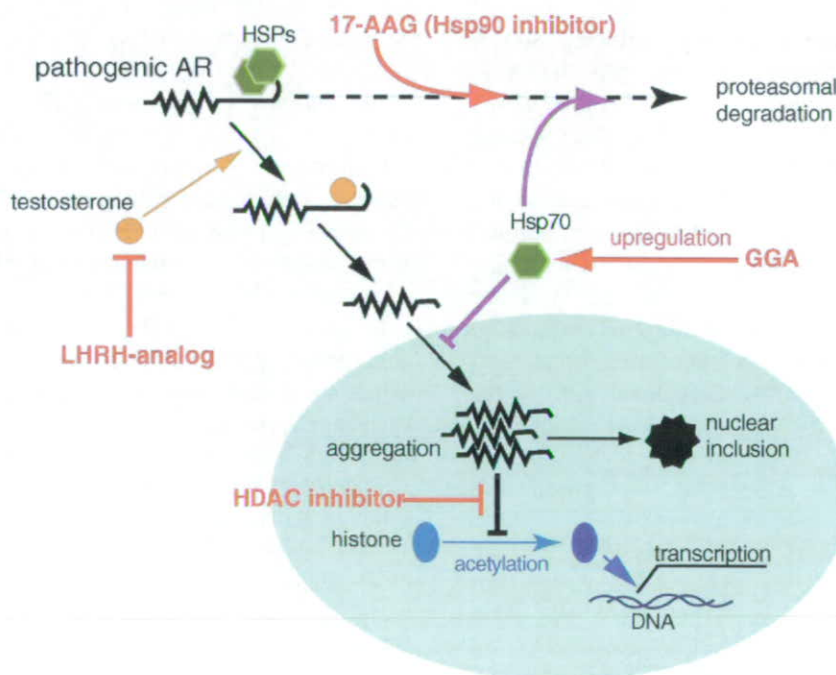


Fig. 4. Pathogenesis-targeting therapeutic approaches to SBMA. In the absence of ligand, the pathogenic AR is confined to a multi-heteromeric inactive complex with heat shock proteins (HSPs) in the cell cytoplasm. Ligand binding facilitates its dissociation from this complex and translocation into the nucleus. In the nucleus, the pathogenic AR forms aggregate and impairs histone acetylation, resulting in transcriptional dysregulation. Several candidates of therapies have been identified on the basis of insights into the molecular mechanisms of the neurodegeneration in SBMA.

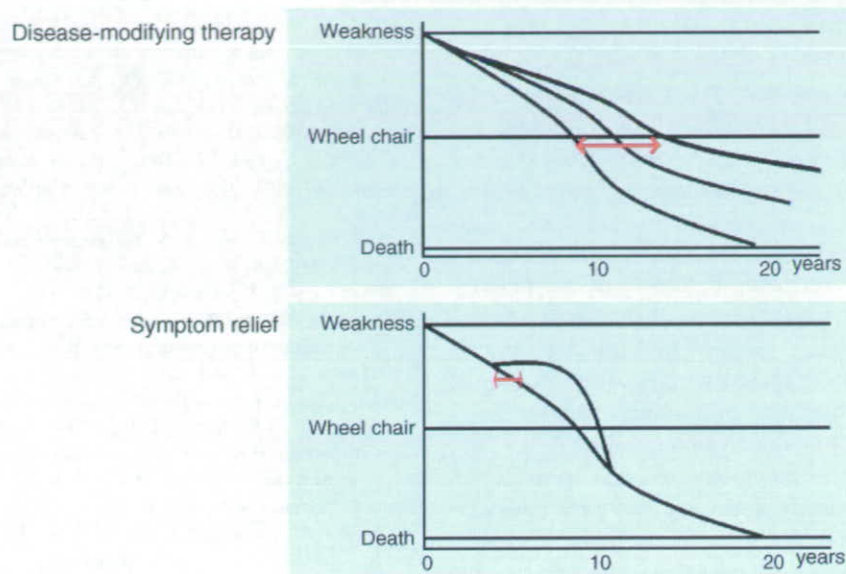


Fig. 5. Disease-modifying therapy and symptom relief. Since the goal of disease-modifying therapy is to inhibit pathogenic progression, long-term trials need to be carried out in order to evaluate drug effects by targeting certain clinical events as the primary endpoint. On the other hand, symptom relief, such as replacement of neurotransmitter, is used to ameliorate symptoms resulting from neurodegeneration. Although trial duration tends to be short, the effect of this therapy is often transient. Arrows indicate trial duration required for each therapy.

inhibitors have been considered to be of therapeutic benefit in polyglutamine diseases (Steffan et al., 2001, Hockly et al., 2003). Butyrate is the first HDAC inhibitor to be discovered, and the related compound, phenylbutyrate, has been successfully employed in experimental cancer therapy. Oral administration of sodium butyrate ameliorates symptomatic and histopathological phenotypes of our mouse model of SBMA through upregulation of histone acetylation in nervous tissues (Minamiyama et al., 2004). Although sodium butyrate is likely to be a promising treatment of SBMA, this compound yielded beneficial effects only within a narrow therapeutic window of dosage in the mouse model. Careful dose determination is mandatory when using HDAC inhibitors for treatment of polyglutamine diseases.

Axonal trafficking defects in SBMA

Motor neurons possess extremely long axon along which molecular motors transport essential components such as organelles, vesicles, cytoskeletons, and signal molecules. This implies that axonal trafficking plays a fundamental role in maintenance of normal function of motor neurons. Obstruction

of axonal transport has gained attention as a cause of neuronal dysfunction in a variety of neurodegenerative diseases including SBMA (Gunawardena and Goldstein, 2005). A mutation in the gene of proteins regulating axonal trafficking, dynein and dynactin 1, has been shown to cause motor neuron degeneration in both human and rodent (Puls et al., 2003; Hafezparast et al., 2003). Experimental data suggest that axonal transport might be retarded by pathogenic polyglutamine-containing AR (Szebenyi et al., 2003). Although this notion is intriguing, its contribution to the pathogenesis of SBMA should be further investigated, since aggregation of the pathogenic AR is rarely found within the axon of motor neurons in patients or model mice.

Clinical application of potential therapeutics

Analysis of cellular and animal models provides insight into mechanisms involved in neurodegeneration of SBMA and indicates retinal therapeutic approaches to this disease (Fig. 4). Therapeutic agent candidates for SBMA are grossly classified into two groups: (i) drugs inhibiting accumulation of the pathogenic AR protein and (ii) drugs mitigating downstream pathological events including

Table 1
Summary of therapeutic trials in SBMA mouse models

Treatment	Number of mice (per treatment group)	Increase in survival (%)	Rotarod task	Body weight	AR accumulation	Reference
Castration	6	>120%	Improved	Improved	Decreased	Katsuno et al. (2002)
Castration ^a	8–9	Not determined	Improved	No effect	Decreased	Chevalier-Larsen et al. (2004)
Leuprorelin	6	>130%	Improved	Improved	Decreased	Katsuno et al. (2003)
Flutamide	6	No effect	No effect	No effect	No effect	Katsuno et al. (2003)
Sodium butyrate	12–15	56%	Improved	Improved	No effect	Minamiyama et al. (2004)
17-AAG	27	>60%	Improved	Improved	Decreased	Waza et al. (2005)
GGA	12–15	>60%	Improved	Improved	Decreased	Katsuno et al. (2005)

^a Treatment is initiated after the onset of motor impairment. AR, androgen receptor; 17-AAG, 17-allylamino geldanamycin; GGA, geranylgeranylacetone.