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Musculoskeletal Pathology

Genetic Background Affects Properties of Satellite Cells and *mdx* Phenotypes

So-ichiro Fukada,* Daisuke Morikawa,* Yukiko Yamamoto,* Tokuyuki Yoshida,* Noriaki Sumie,* Masahiko Yamaguchi,* Takahito Ito,* Yuko Miyagoe-Suzuki,† Shin'ichi Takeda,† Kazutake Tsujikawa,* and Hiroshi Yamamoto*

From the Department of Immunology, Graduate School of Pharmaceutical Sciences, Osaka University, Osaka; and the Department of Molecular Therapy,† National Institute of Neuroscience, National Center of Neurology and Psychiatry, Tokyo, Japan*

Duchenne muscular dystrophy (DMD) is the most common lethal genetic disorder of children. The *mdx* (C57BL/10 background, C57BL/10-*mdx*) mouse is a widely used model of DMD, but the histopathological hallmarks of DMD, such as the smaller number of myofibers, accumulation of fat and fibrosis, and insufficient regeneration of myofibers, are not observed in adult C57BL/10-*mdx* except for in the diaphragm. In this study, we showed that DBA/2 mice exhibited decreased muscle weight, as well as lower myofiber numbers after repeated degeneration–regeneration cycles. Furthermore, the self-renewal efficiency of satellite cells of DBA/2 is lower than that of C57BL/6. Therefore, we produced a DBA/2-*mdx* strain by crossing DBA/2 and C57BL/10-*mdx*. The hind limb muscles of DBA/2-*mdx* mice exhibited lower muscle weight, fewer myofibers, and increased fat and fibrosis, in comparison with C57BL/10-*mdx*. Moreover, remarkable muscle weakness was observed in DBA/2-*mdx*. These results indicate that the DBA/2-*mdx* mouse is a more suitable model for DMD studies, and the efficient satellite cell self-renewal ability of C57BL/10-*mdx* might explain the difference in pathologies between humans and mice. ***(Am J Pathol 2010, 176:2414–2424; DOI: 10.2353/ajpath.2010.090887)***

Duchenne muscular dystrophy (DMD) is a progressive and lethal X-linked muscular disorder caused by mutations in the dystrophin gene.[1] The dystrophin gene encodes a 427-kDa cytoskeletal protein that forms the dystrophin/glycoprotein complex at the sarcolemma with α- and β-dystroglycans, α-, β-, γ-, and δ-sarcoglycans, and other molecules, and links the cytoskeleton of myofibers to the extracellular matrix in skeletal muscle.[2,3] The lack of dystrophin in the sarcolemma disturbs the assembly of the dystrophin/glycoprotein complex and causes instability of the muscle membrane, leading to muscle degeneration and myofiber loss. The histopathological hallmarks of DMD include degeneration, necrosis, accumulation of fat and fibrosis, and insufficient regeneration of myofibers accompanied by a loss of myofibers.[4] Therefore, the manifestations of DMD are considered to result from an imbalance between degeneration and regeneration.

The function and structure of dystrophin has been elucidated by studies of a variety of dystrophin-deficient animals. Among these animal models, the *mdx* mouse (the correct nomenclature is C57BL/10-*Dmd*^{mdx}), first described in1984, is the most prolific. A spontaneous mutation (*mdx*) arose in an inbred colony of C57BL/10 mice, which have a high level of serum pyruvate kinase.[5] The muscle pathology of the mice includes active fiber necrosis, cellular infiltration, a wide range of fiber sizes, and numerous centrally nucleated regenerating fibers. However, in contrast to DMD, replacement of muscle with fat and fibrosis is not prominent, and no losses of muscle fiber and muscle weight are observed in the skeletal muscle of *mdx* mice except in the diaphragm.[6,7] In contrast, most of the limb muscles of the *mdx* mouse maintain hypertrophy and increased skeletal muscle mass throughout much of their life span.[8] One reason for the difference between DMD and *mdx* is explained by the up-regulation of expression of utrophin, a homolog of dystrophin.[9,10] Another reason has been supposed to be the excellent regeneration capacity of *mdx* com-

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S.F. and D.M. contributed equally to this work.

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Address reprint requests to So-ichiro Fukada, Ph.D., Department of Immunology, Graduate School of Pharmaceutical Sciences, Osaka University, 1-6 Yamada-oka, Suita, Osaka 565-0871, Japan. E-mail: fukada@phs.osaka-u.ac.jp.

pared with DMD. However, this hypothesis has not been verified.

Regeneration of skeletal muscle depends on the competence of muscle satellite cells. Muscle satellite cells, which account for 2 to 5% of the total nuclei in adult skeletal muscle, play a major role in muscle regeneration.[11] Under normal conditions, satellite cells are found external to the myofiber plasma membrane and beneath the muscle basal lamina,[12] and they are mitotically quiescent in adult skeletal muscle.[13] When activated by muscle damage, satellite cells proliferate, differentiate, fuse with each other or injured myofibers, and eventually regenerate mature myofibers. During the regenerative processes, satellite cells not only produce large amounts of muscle, but also renew themselves to maintain their own population.[14] In fact, it is reported that the satellite cell pool of C57BL/10 continues to respond efficiently even when the skeletal muscle is subjected to as many as 50 cycles of severe damage.[15] Therefore, it is thought that maintenance of the satellite cell pool is indispensable to retain the long-term regenerative potential for skeletal muscle injury, including in muscular dystrophies.

To investigate genetic differences in long-term regeneration potential, we first induced repeated degeneration–regeneration cycles in four inbred strains of mice. Among these strains, C57BL/6, a widely used strain akin to C57BL/10, was tolerant of repeated injury. This is consistent with the results of C57BL/10 previously described.[15] In contrast, among four inbred strains, DBA/2 mice exhibited the most remarkable skeletal muscle loss and impaired regeneration after repeated injury. Importantly, the self-renewal potential of DBA/2 satellite cells was significantly lower than that of C57BL/6. In addition, *in vitro* colony formation and proliferation assays indicated that intrinsic difference between C57BL/6 and DBA/2 satellite cells exist. Finally, we crossed the *mdx* genotype with the DBA/2 for more than five generations. At the fifth backcross, the mice are not yet fully congenic (D2.B10-*DMD*^{mdx}), and thus we refer to them as DBA/2-*mdx* hereafter. We investigated their phenotypes. Intriguingly, severe loss of skeletal muscle weight, decreased myofiber number, increased fat and fibrosis volume, and apparent muscle weakness were observed in the DBA/2-*mdx* mice. These results indicate that the intrinsic genetic program affects the properties of satellite cells, and DBA/2-*mdx* will be a more useful model of DMD than C57BL/10-*mdx*. It is also speculated that the high self-renewal potential of C57BL/10 satellite cells might explain the difference in pathologies between humans and mice.

Materials and Methods

Mice

Six-week-old, specific pathogen-free, BALB/c, C3H/HeN, C57BL/6, and DBA/2 mice were purchased from Charles River Japan (Yokohama, Japan). Six-week-old, specific pathogen-free C57BL/10 mice were purchased from Shimizu Laboratory Supplies Co., Ltd (Kyoto, Japan). Specific pathogen-free *mdx* mice (of C57BL/10 background) were provided by Central Laboratories of Experimental Animals (Kanagawa, Japan) and maintained in our animal facility by brother-sister matings. *Mdx* of C57BL/10 background were backcrossed into DBA/2 genetic background. Mice backcrossed more than five generations were used in this study. Genotyping was performed according to previous reports.[16] All procedures for experimental animals were approved by the Experimental Animal Care and Use Committee at Osaka University.

Muscle Injury

Muscle injury was induced by injecting cardiotoxin (10 μmol/L in saline, Wako Pure Chemical Industries, Tokyo, Japan) into tibialis anterior (50 μl), gastrocnemius (150 μl), and quadriceps femoris (100 μl) muscles as described.[17] All injections were first done when mice were 8 to 10 weeks of age.

Histological Analysis

Tibialis anterior, gastrocnemius, and quadriceps femoris muscles were isolated and frozen in liquid nitrogen-cooled isopentane (Wako Pure Chemical Industries). Cryosections (10 μm) were stained with H&E, Oil red-O (Sigma-Aldrich, St. Louis, MO), or Sirius Red (Sigma-Aldrich).

Immunohistochemistry

For immunohistochemical examinations, transverse cryosections (6 μm) were stained with various antibodies. Monoclonal rat anti-laminin α2 (1:200; clone: 4H8-2) and mouse anti-Pax7 antibodies were purchased from Alexis Biochemical (Lausen, Switzerland) and Developmental Studies Hybridoma Bank (Iowa, IA), respectively. For Pax7 staining, a M.O.M. kit (Vector Laboratories, Burlingame, CA) was used to block endogenous mouse IgG. After the first staining at 4°C overnight, sections were reacted with secondary antibodies conjugated with Alexa 488 or Alexa 568 (Molecular Probes, Eugene, OR). Sections were shielded using Vectashield (Vector Laboratories, Inc). The signals were recorded photographically using an Axiophot microscope (Carl Zeiss, Oberkochen, Germany).

Preparation of Muscle Satellite Cells and Culture

Satellite cells were isolated from uninjured adult skeletal muscle using biotinylated-SM/C-2.6[18] and IMag methods (BD Immunocytometry Systems, Mountain View, CA) as described in a previous report.[17] Satellite cells were cultured in a growth medium of high-glucose Dulbecco's modified Eagle's medium (Sigma-Aldrich) containing 20% fetal calf serum (Trace Biosciences, N.S.W., Australia), 2.5 ng/ml basic fibroblast growth factor (PeproTech, London, UK), leukemia inhibitory factor (Alexis Biochemical), and penicillin (100 U/ml)-streptomycin

(100 μg/ml) (Gibco BRL, Gaithersburg, MD) on culture dishes coated with Matrigel (BD Bioscience, San Diego, CA).

Colony Forming Assay

Clonal cultures of freshly isolated satellite cells were performed in 96-well plates coated with type I collagen (Sumilon, Tokyo, Japan) in growth medium for a week. The frequency of colony formation and number of cells in each well were counted under a phase-contrast microscope.

Cell Proliferation Assay

Isolated satellite cells were cultured in growth medium for 3 to 4 days, and expanded primary myoblasts were harvested and additional culture was performed in 96-well dishes for 1 day. Eight hours later, bromodeoxyuridine (BrdU) uptake was quantified using the Cell Proliferation ELISA, BrdU Kit (Roche Diagnostics, Basel, Switzerland) and a microplate reader (Model 680, Bio-Rad, Hercules, CA).

Measurement of Sizes of Myofibers and Oil Red-O-Positive and Fibrotic Areas

Image J software was used to measure myofiber sizes and Oil red-O- and Sirius Red-positive areas.

Evans Blue Dye Injection

Evans blue (Wako Pure Chemical Industries) was dissolved in PBS and injected intraperitoneally into mice (1 mg/100 μl/10g body weight).[19] Sixteen to 18 hours later, muscle tissues were removed, and frozen in liquid nitrogen-cooled isopentane. The muscle fibers with Evans Blue incorporated were then counted as injured muscles.

Muscle Endurance and Grip Strength Test

The muscle endurance test was referred to the studies by Handschin et al.[20] In brief, we used a MK-680S treadmill (Muromachi Kikai Co., Ltd., Tokyo, Japan). For 3 days, animals were acclimated to treadmill running for 5 minutes at a speed of 10 m/min on a 0% grade. After the acclimation, animals ran on a treadmill with a 10% uphill grade starting at a speed of 10 m/min for 5 minutes. Every subsequent 2 minutes, the speed was increased by 2 m/min until the mice were exhausted. Exhaustion was defined as the inability of the animal to remain on the treadmill despite mechanical prodding. Running time and speed were measured, and the distance was calculated. Grip strength was measured using a MK-380M grip strength meter (Muromachi Kikai Co., Ltd). The grip strength of each individual mouse was measured 10 times, the same measurements were repeated on the next day, and the highest value of each experiment was used.

Statistics

Values were expressed as means ± SD. Statistical significance was assessed by Student's *t*-test. In comparisons of more than two groups, nonrepeated measures analysis of variance (analysis of variance) followed by the Student-Newman-Keuls test were used. A probability of less than 5% ($P < 0.05$) or 1% ($P < 0.01$) was considered statistically significant.

Results

Genetic Differences in Skeletal Muscle Regeneration

To examine the long-term regeneration ability of four inbred strains of mice, repeated cycles of degeneration–regeneration were induced by injection of cardiotoxin (CTX). CTX was injected into one side of the tibialis anterior (TA), gastrocnemius (GC), and quadriceps (Qu) muscle every 2 weeks. At the last (sixth) CTX injection, another intact TA muscle received CTX once to examine the regenerative potential in one cycle of each mouse at this age. Four weeks later, the muscles were removed and analyzed. As shown in Figure 1, A and B, none of the strains displayed a striking difference in either skeletal muscle weight or histochemistry after one CTX injection (CTX-1), except for the appearance of adipocytes in BALB/c. However, the DBA/2 mice that received six CTX injections (CTX-6) exhibited remarkably impaired regeneration (Figure 1A) and loss of TA muscle weight (Figure 1B). A similar loss of muscle weight was also observed in GC and Qu of DBA/2 (CTX-6 in Figure 1C). In contrast, none of the other strains showed a significant difference in uninjured muscle weight at this age (uninjured in Figure 1C). Fat was observed in DBA/2, BALB/c, and C3H/HeN after six injections, but the sclerosis and loss of muscle weight was remarkable in DBA/2. Therefore, the following experiments were performed on C57BL/6 and DBA/2.

Regeneration Impairment in DBA/2 Is Inherited Recessively

To assess the inheritance of the lower regeneration ability of DBA/2, we injected CTX into C57BL/6, DBA/2, and their F1 mice (B6D2F1). To allow more sufficient regeneration time, the interval between CTX injections was changed to 4 weeks. As shown in Figure 2A, we found marked muscle weight loss in DBA/2 after three CTX injections (4 weeks × 3). The results of B6D2F1 mice were similar to those of C57BL/6 (Figure 2, A and B).

As shown in Figure 1A, DBA/2 mice exhibited impaired regeneration accompanied by accumulation of fat and fibrosis after three CTX injections (4 weeks × 3), but not in the 4 weeks × 1 experiment (Figure 2B). Oil red-O (Figure 2C) and Sirius Red (Figure 2D) stainings were performed to determine the amount of fat and fibrosis, respectively. As shown in Figure 2E, increments in fat and fibrotic areas were observed in DBA/2 mice receiving

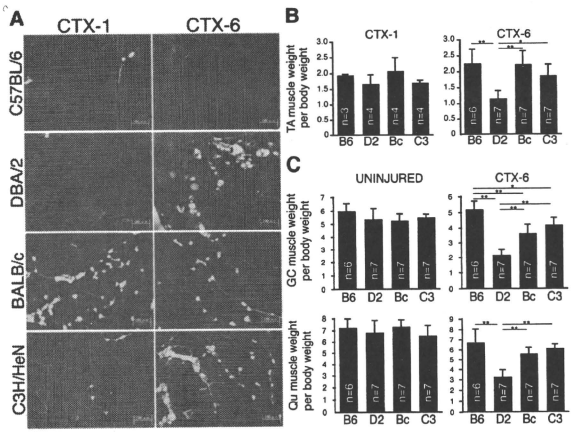

Figure 1. Impaired regeneration and loss of muscle weight in DBA/2 mice after injured six times. **A:** TA (tibialis anterior) muscles were examined histologically in four inbred strains of mice after one (CTX-1) or six (CTX-6) cardiotoxin (CTX) injections. The cross sections were stained with H&E. Scale bar = 100 μm. **B:** The TA muscle weight (mg) per body weight (g) in each inbred strain after one or six CTX injections. B6, D2, Bc, and C3 indicate C57BL/6, DBA/2, BALB/c, and C3H/HeN mice, respectively. **C:** The GC (gastrocnemius) and Qu (quadriceps) muscle weights (mg) per body weight (g) in each inbred strain from uninjured or muscle injured six times. The number in the each graph indicates the number of mice used in these experiments. $^{*}P < 0.05$, $^{**}P < 0.01$ (analysis of variance, SNK-test).

three injections (4 weeks × 3). In 4 weeks × 1 DBA/2, the fat accumulation of one mouse was a slightly higher volume (2.02%), but three mice showed little fat accumulation (less than 0.6%). In contrast to DBA/2, C57BL/6, and B6D2F1 mice did not show any sign of impaired regeneration. These results indicate that the impaired regeneration ability of the DBA/2 strain after repeated injury is recessive heredity.

Loss of Muscle Mass Results from Decreased Number and Size of Myofibers

To assess the cause of muscle weight loss in DBA/2, the numbers and sizes of myofibers were quantified. In uninjured muscle, no significant difference between the numbers of myofibers was observed in C57BL/6 and DBA/2 (Figure 3A). However, as shown in Figure 3B, decreased numbers of myofibers were observed in DBA/2 after three CTX injections (4 weeks × 3), as compared with 4 weeks × 1 or uninjured muscle. C57BL/6 showed more myofibers than uninjured muscle after one or three injections (Figure 3B).

The sizes of myofibers were also measured. Four weeks after one CTX injection (4 weeks × 1), the size of myofibers in DBA/2 was similar to that in C57BL/6 (Figure 3, C and D). However, the regenerated myofibers of DBA/2 (4 weeks × 3) were slightly smaller than those of C57BL/6 (Figure 3, C and D). These data indicate that the loss of muscle weight in DBA/2 results from the decreased number and size of myofibers.

Decreased Number of Self-Renewed Satellite Cells in DBA/2

We hypothesized that a decreased number of satellite cells leads to the loss of myofibers, because myofibers are mainly made by satellite cells. To elucidate this hypothesis, we examined the number of satellite cells. As shown in Figure 3E, cells positive for Pax7, a specific marker of satellite cells,[21] lying beneath the basal lamina were counted. There was no significant difference between the uninjured TA muscles of C57BL/6 and DBA/2 mice. However, a remarkable decrease in the number of satellite cells was observed in DBA/2 after three CTX injections (Figure 3F). These results imply that the functions (including self-renewal potential) of satellite cells include responsibility for most of the regeneration of impaired muscle in DBA/2.

Colony Formation and Proliferation of Satellite Cells from DBA/2

To examine whether there is an intrinsic difference between the satellite cells of C57BL/6 and DBA/2, satellite cells were isolated and cultured *in vitro*. As shown in Figure 4A, the BrdU uptake of primary myoblasts of DBA/2 was inferior to that of C57BL/6 myoblasts. Next, we performed a colony-forming assay of single satellite cells. As shown in Figure 4C, single DBA/2 satellite cell did not produce large colonies similar to those of C57BL/6. The frequencies of colony forming cells did not differ in C57BL/6 and DBA/2 (Figure 4B). These results indicate that intrinsic factors affect the properties of satellite cells.

*Loss of Muscle Weight in DBA/2-*mdx

To assess whether the low regenerative potential of mice with the dystrophin mutation exhibit DMD-like features, we crossed C57BL/10-*mdx* (B10-*mdx*) into DBA2. It was reported that body weight of B10-*mdx* is heavier than that of the control wild-type.[22] In contrast to B10-*mdx*, DBA/

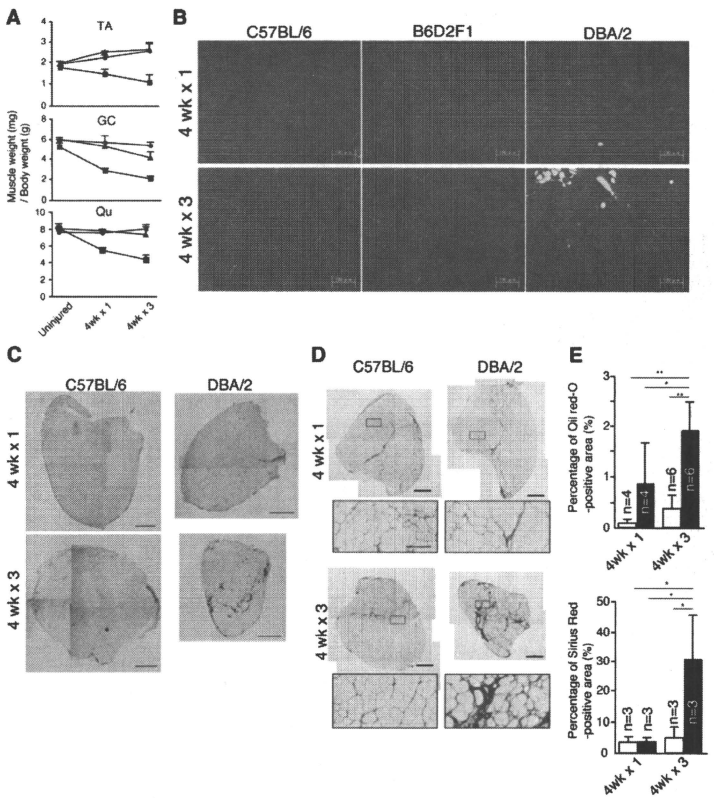

Figure 2. Impaired regeneration of DBA/2 phenotype is recessively inherited. **A:** The TA, GC, and Qu muscle weights (mg) per body weight (g) in C57BL/6 (closed circles), DBA/2 (closed squares), and B6D2F1 (closed triangles) mice after one (4 weeks × 1) or three CTX injections (4 weeks × 3). The cross sections were stained with H&E (**B**), Oil red-O (**C**), or Sirius Red (**D**). Scale bars: 100 μm (**B**); 500 μm (**C** and **D**). **E:** The *y* axis shows the mean percentage of Oil red-O or Sirius Red-positive areas per section. White and black columns indicate the results of C57BL/6 and DBA/2, respectively. The number in the each graph indicates the number of mice used in this analysis. $^{*}P < 0.05$, $^{**}P < 0.01$ (analysis of variance, SNK-test).

2-*mdx* (D2-*mdx*) mice showed the decreased body weight regardless of gender (Figure 5A). A more remarkable phenotype of D2-*mdx* was the loss of skeletal muscle mass (Figure 5B). As previously reported, the muscle weight of B10-*mdx* was heavier than that of controls,[8] but the TA, GC, and Qu muscle weights of D2-*mdx* males were 71%, 59%, and 54% of those of controls, respectively (Figure 5C). Female muscles were 85% (TA), 61% (GC), and 52% (Qu) of each control muscle, respectively. The loss of muscle weight did not simply reflect the decreased body weight because there is also a significant difference in muscle weight (mg) per body weight (g) between D2-*mdx* and control littermates (Figure 5C). Control littermates of D2-*mdx* and normal DBA/2 exhibited similar results in muscle weight per body weight ratios (data not shown).

Histology of DBA/2-mdx

In contrast to the histology of DMD, it is widely accepted that fibrosis and fat replacement are minimal in B10-*mdx*.[7] In addition, there was no apparent fiber loss. To examine the accumulation of fibrosis and fat tissue in D2-*mdx*, cross sections were stained with Sirius Red or Oil red-O. As shown in Figure 6, A and B, there was no sign of fibrosis or adipogenesis in B10-*mdx*. However, D2-*mdx* mice exhibited increased fibrosis and fat accu-

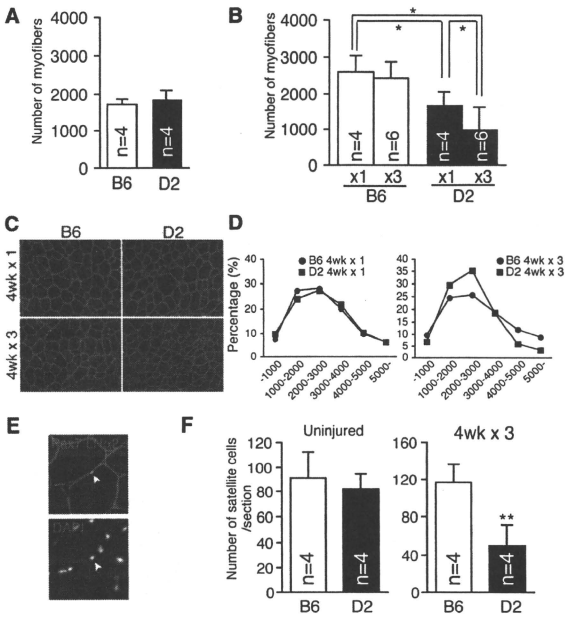

Figure 3. Decreased numbers of myofibers and satellite cells in DBA/2 mice after three repeated injuries. **A:** The number of myofibers in uninjured TA muscle at 10 weeks old. The *y* axis shows the mean number of myofibers per section. B6 and D2 indicate C57BL/6 and DBA/2, respectively. **B:** The mean numbers of myofiber in TA muscles after one or three injuries. $^{*}P < 0.05$ (analysis of variance, SNK-test). The sizes of myofibers in TA muscle after one or three CTX injections. **C:** Cross sections were stained with anti-laminin α2 antibody (green). **D:** The size of each myofiber in TA muscle was measured after one or three injections. Closed circles or squares show the results of C57BL/6 or DBA/2, respectively. **E: Arrowhead** indicates Pax7 expressing cells lying beneath the basal lamina. **F:** The number of satellite cells in noninjured TA muscle (uninjured) or TA muscle injured three times (4 weeks × 3). The *y* axis shows the mean number of satellite cells per section. The number in each graph indicates the number of mice used in these analyses. $^{**}P < 0.01$ (Student's *t*-test).

mulation in comparison with B10-*mdx*. In contrast to B10-*mdx*, a decreased number of total myofibers was also observed in D2-*mdx* (Figure 6C).

To enumerate the number of necrotic fibers, the mice were injected with Evans blue dye to visualize necrotic fibers. As shown in Figure 6C, fewer total necrotic fibers were observed in D2-*mdx*. This result suggests that the D2-*mdx* phenotype does not result from acceleration of degeneration.

Decreased Skeletal Muscle Function in DBA/2-mdx

Skeletal muscle endurance was assessed by treadmill running to exhaustion as an indicator of maximal muscle capacity. After acclimatization, mice were run on a 10% slope at increasing speed until the animals were unable to remain on the treadmill despite prodding. We then recorded the end time and speed to calculate the distance run. As shown in Figure 7A, male and female D2-*mdx* ran 45% and 56% shorter distances than control littermates. The maximum speed of D2-*mdx* was also lower than that of their littermate. The distance run showed the most significantly difference because of the protocol of increasing speed (Figure 7A). The average distance run by male controls was 544 meters, but that of D2-*mdx* males was 205 meters (38% of the control). A similar result was shown by female D2-*mdx* (25% of the control). B10-*mdx* also showed lower values compared with normal C57BL/10 mice (data not shown), but the decreased ratio of each parameter in D2-*mdx* was more remarkable than that in B10-*mdx* (Figure 7B).

A grip strength test was also performed as an indicator of motor function and whether D2-*mdx* exhibited muscle weakness compared with controls. As shown in Figure 7C, D2-*mdx* earned a lower score than control mice regardless of gender. However, there was no significant difference between B10-*mdx* and control mice.

Discussion

Repeated Injury Models

Muscle satellite cells play central roles in skeletal muscle regeneration.[23] Satellite cells produce a vast number of progenitor cells (myoblasts) that finally become myofibers. During this process, at least some of the satellite cells have self-renewal potential,[14,24] but are quiescent and will respond efficiently to the next damages. In fact, Luz et al[15] indicated that C57BL/10 could regenerate after 50 bupivacaine injections without the loss of myofibers or gain of fibrotic areas in the TA muscle. Importantly, C57BL/10-*mdx* mice exhibited decreased numbers of myofibers after 50 bupivacaine injections[15]

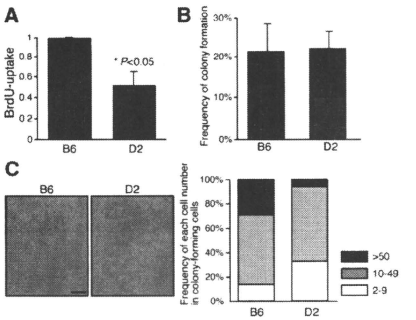

Figure 4. Satellite cells of DBA/2 strain show inferior BrdU uptake and colony-forming potential. **A:** BrdU uptake of primary myoblasts derived from C57BL/6 or DBA/2 satellite cells. The *y* axis shows the mean with SD of three independent experiments. $*P < 0.05$ (Student's *t*-test). Frequency of colony formation by a single satellite cell derived from C57BL/6 or DBA/2 (**B**) and the size of single cell-derived colonies (**C**). The picture shows representative colonies of each strain. Colonies were categorized into three groups: >50 cells/well, 10 to 49 cells/well, and 2 to 9 cells/well. The *y* axis indicates the frequency (**B**) or percentage of each category (**C**) from three independent experiments. Scale bar = 100 μm.

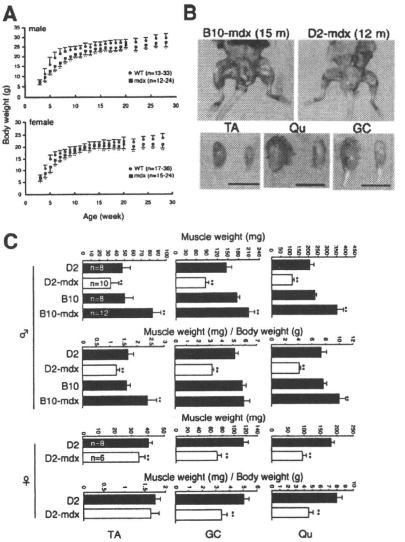

Figure 5. DBA/2-*mdx* mice show decreased body weight and remarkable muscle weight loss. **A:** Body weight of D2-*mdx* (closed squares) and their wild or heterozygous littermates (open circles) related to age. $*P < 0.05$, $**P < 0.01$ (Student's *t*-test) **B:** Photographs of hind limb muscles of male B10-*mdx* (15 months) and D2-*mdx* (12 months). Scale bar = 1 cm. **C:** TA, GC, and Qu muscle weights (mg) or per body weight (g) of 6-month-old mice. *x* axis shows the mean with SD. The numbers of muscles used in each study are shown in each graph. $*P < 0.05$, $**P < 0.01$.

because C57BL10-*mdx* mice already have dystrophic degeneration–regeneration cycles. Sadeh et al[25] also showed active regeneration cycles in rats that received weekly injections of bupivacaine for 6 months. They reported that there was lack of evidence for reduction or exhaustion of muscle fiber capacity to regenerate despite ongoing degeneration–regeneration over a period approximating one fourth of the rat life expectancy. These results indicate that the satellite cell pool was efficiently maintained for multiple degeneration–regeneration cycles in these animals, and that dystrophic mice exhibit less regeneration ability. However, DBA/2 showed significantly decreased numbers of myofibers and self-renewed satellite cells after only three injections of CTX.

The number of DBA/2 satellite cells in uninjured TA muscle is similar to that of C57BL/6. Although, the myofibers in DBA/2 were smaller than those in C57BL/6 2 weeks after one CTX injection (data not shown), the myofiber size and histological characteristics showed few significant differences between and DBA/2 and C57BL/6 4 weeks after a single CTX injection. These results suggest that the self-renewal ability of DBA/2 satellite cells is incomplete and that the exhaustion of muscle satellite cells leads to a decreased number of myofiber and loss of skeletal muscle weight. Nonmyogenic cells, for example, macrophages, also play important roles in skeletal muscle regeneration. However, dysfunction of macrophages leads to impaired regeneration after one CTX injection.[26,27] Furthermore, the remarkable regeneration deficit was not observed in DBA/2 4 weeks after one CTX injection in TA muscle. These results suggest that repeated injury is a suitable model to assess the long-term regeneration potential of skeletal muscle, and that the self-renewal ability of satellite cells is responsible at least in part for the result of repeatedly injured muscle in DBA/2.

Strain Differences of Muscle Regeneration Ability

C57BL/6, a strain akin to C57BL/10, is the most widely used strain for skeletal muscle regeneration studies. As shown in Figure 1, C57BL/6 has the best ability to regenerate skeletal muscle among the four inbred strains examined. An early study by Grounds and McGeachie[28] indicated a strain difference in skeletal muscle regeneration between BALB/c and Swiss SJL/J. They showed that superior and faster regeneration was observed in the Swiss SJL/J strain. The most outstanding phenotype of DBA/2 is the remarkable decrease of muscle weight compared with the three other inbred strains, including BALB/c. Intriguingly, DBA/2 mice have a shorter life span than C57BL/6.[29] In addition, it is reported that muscle weight loss is increased during aging (sarcopenia) in DBA/2 mice compared with C57BL/6.[30] The reason why the DBA/2 strain exhibits the loss of muscle weight is unknown, but our results imply a relationship between

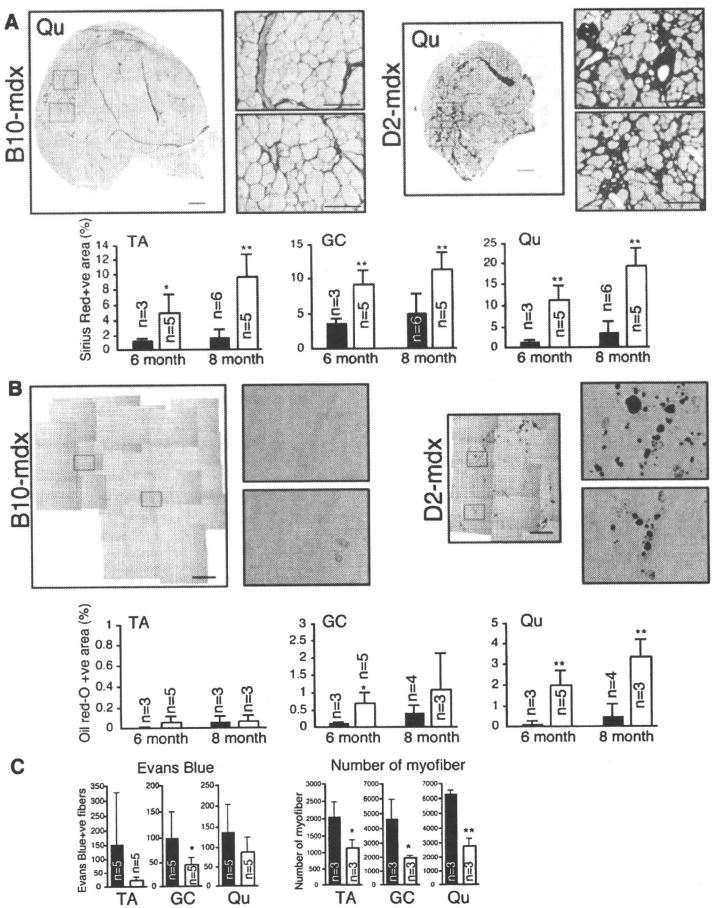

Figure 6. Histological analyses of DBA/2-*mdx* mice. Sirius red staining (**A**) and Oil red-O staining (**B**) of Qu muscle of 8-month-old B10-*mdx* and D2-*mdx* mice. The *y* axis indicates the mean percentage of Sirius Red- (**A**) or Oil red-O (**B**) -positive areas per section. The *x* axis indicates the age of mice. Black and white columns show the results for B10-*mdx* and D2-*mdx*, respectively. The numbers of mice used in each study are shown in each graph. **C:** The *y* axis indicates the mean number of Evans blue-positive or total myofibers of B10-*mdx* and D2-*mdx* at 8 months of age. $^{*}P < 0.05$, $^{**}P < 0.01$.

the impaired function of satellite cells and sarcopenia in DBA/2.

Heydemann et al[31] reported that γ-sarcoglycan-null mice with DBA/2 background showed decreased skeletal muscle weight, increased Evans Blue uptake, and a higher hydroxyproline concentration than C57BL/6, CD1, and 129 background null mice. Although they ruled out the voluntary activities of DBA/2, they did not discuss the cause of these results. Our results suggest that the low regeneration potential of DBA/2 leads to a severe skeletal muscle phenotype in various dystrophic mouse models.

The DBA/2J strain has been used in sarcopenia and γ-sarcoglycan-null mouse studies.[30,31] To exclude the possibility that DBA/2 substrain differences exist, we compared the BrdU uptake of primary myoblasts in DBA/2N (used in this study) and DBA/2J. Because we observed similar low BrdU uptakes by primary myoblasts in both DBA/2N and DBA/2J (data not shown), these

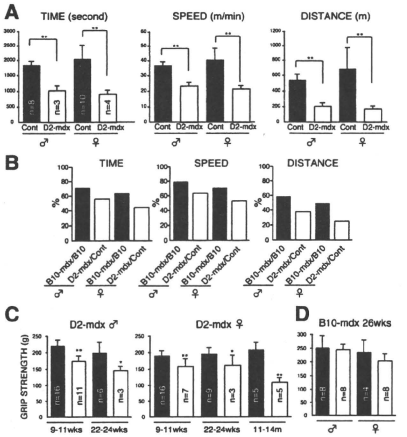

Figure 7. Comparison of muscle strength in DBA/2-*mdx* and B10-*mdx*. **A:** Treadmill running test of mice at 24 weeks old. Final time, speed, and distance were recorded and calculated for the individual performance score. The averages are shown with SD. Control indicates heterozygous or wild-type littermates of D2-*mdx*. The numbers of mice used in each study are shown in each graph. $^{*}P < 0.05$, $^{**}P < 0.01$. **B:** Comparison of C57BL/10-*mdx* and DBA/2-*mdx* in treadmill running test. The *y* axis indicates the percentage of *mdx* per control value. The numbers of male C57BL/10, male C57BL/10-*mdx*, female C57BL/10, and female C57BL/10-*mdx* are 4, 4, 4, and 8, respectively. Grip strength test of D2-*mdx* (**C**) or B10-*mdx* (**D**). Black and white columns indicate the results for *mdx* or control mice, respectively. The *y* axis indicates the average score of each mouse with SD. The *x* axis shows the ages of mice. The number in the each graph indicates the number of mice taking this test. $^{*}P < 0.05$, $^{**}P < 0.01$.

results suggest that lower muscle regeneration is common to the DBA/2 strain.

Stem (Satellite) Cell Function and Mouse Strains

As mentioned above, some previous reports indicated different responses in skeletal muscle regeneration among inbred strains of mice. However, to our knowledge, this is the first evidence that there is an intrinsic difference in satellite cells among inbred mice. The exact relationship between *in vitro* and *in vivo* results of satellite cells is not clear. However, low or slow proliferation of satellite cells might explain the decreased muscle weight and slow regeneration after a single injury in DBA/2 in comparison with C57BL/6 and B6D2F1, which showed increased muscle weight in their TA muscle (Figure 2A). It is unlikely that telomere erosion contributes to the *in vitro* and *in vivo* results of DBA/2 satellite cells because DBA/2 mice have longer telomeres than C57BL/6 mice.[32]

Recently Kuang et al[33] reported that satellite cells are a heterogeneous population of stem cells (satellite stem cells) and committed progenitor cells, and that they can be distinguished from others by Myf5 expression. They showed that Myf5-negative (satellite stem) cells self-renewed three times more frequently than Myf-5-positive (progenitor) cells *in vivo*. Schultz and Lipton[34] first described the heterogeneity of satellite cells by the different colony sizes of each satellite cell and found decreased colony sizes in aging muscle in the rat. Although it was not determined whether satellite stem cells form a large-colonies or not *in vitro*, our results showed that mice having low self-renewing satellite cells (DBA/2) exhibit smaller colony formations than mice having high self-renewing satellite cells (C57BL/6). These results suggest that satellite stem cells may form larger colonies *in vitro*.

In contrast to satellite cells, a highly strain-dependent function of hematopoietic stem cells was reported.[35] Chen et al[36] reported that DBA/2 showed a decline in primitive hematopoietic stem cell function with age, but that it increased with age in C57BL/6 in a *vivo* transplantation study. Recombinant inbred mice, named BXD strains, are available. Using BXD, Liang et al[37] identified latexin as affecting the size of the hematopoietic stem cell population in mice. A similar approach might lead to the discovery of key genes that affect the properties of satellite cells.

DBA/2-mdx *as Model for DMD*

Mdx was discovered a quarter of a century ago.[5] In 1989, the *mdx* mutation, a C to T transition within exon 23, was identified in the dystrophin gene on the X chromosome.[38] Nearly all *mdx* colonies are maintained as homozygous inbred lines; in addition, the difficulty of point mutation typing might impede the effect of genetic background on *mdx* phenotype. However, Amalfitano and Chamberlain[16] reported a rapid and simple typing strategy, and we established DBA/2-*mdx* following their protocol. C57BL/10-*mdx* mice have played central roles in a vast array of pathological, clinical, and physiological studies as a model for DMD. However, they do not reflect human pathology in some aspects, including little fat and fibrosis accumulation, no loss of myofiber numbers, and muscle weight. Recently, Gargioli et al[39] showed that the advanced stage of dystrophy including sclerosis precluded treatment by stem cell therapy. Therefore, assessment of therapeutic effect in more severe disease conditions is needed.

In marked contrast to the severe phenotype observed in DMD, early studies using C57BL/10-*mdx* concluded that they do not show obvious functional disability.[5,7] However, some later reports indicated functional differences between C57BL/10-*mdx* and control mice.[40–43] As shown in Figure 7, C57BL/6-*mdx* also showed muscle weakness in the treadmill test. However, the muscle weakness of DBA/2-*mdx* is more remarkable than that of C57BL/10-*mdx*. Therefore, DBA/2-*mdx* is a more appropriate model to assess skeletal muscle function after therapeutic treatment.

Chamberlain et al[44] reported that the average life spans of female and male C57BL/10-*mdx* mice were 22.5 and 21.5 months, respectively. Pastoret et al[8] also reported that C57BL/10-*mdx* mice have short life spans and that C57BL/10-*mdx* older than 78 weeks exhibit progressive weakness. We have not determined the life span of DBA/2-*mdx*, but it will be clarified in the future. Intrigu-

ingly, Chamberlain et al[44] observed the appearance of rhabdomyosarcoma-like tumors in C57BL/10-*mdx*. They speculate that the lifelong continuous myofiber degeneration and regeneration that characterize this animal model are associated with continuous and massive activation and proliferation of satellite cells, which greatly increase the chance of developing random and spontaneous mutations. To date, we have observed tumors in C57BL/10-*mdx* but not in DBA/2-*mdx*. This observation supports their speculations.

The reasons why *mdx* mice do not show the human-like pathology have been investigated. One reason for the difference between DMD and *mdx* is explained by the presence of utrophin, a homolog of dystrophin. Utrophin is located in the neuromuscular junction in normal muscle. In dystrophic muscle, utrophin is up-regulated in the sarcolemma and compensates for dystrophin function. As shown in Figure 6, the results of Evans blue uptake in DBA/2-*mdx* indicated that the degeneration of myofiber was not accelerated, but that the regeneration potential was inferior. These results clearly indicate that not only utrophin expression but also regeneration potential, perhaps a satellite cell function, directly leads to the pathological condition. The identification of genes that determine the DBA/2 phenotype will provide new therapeutic strategies for the treatment of muscular dystrophy.

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