uPA deficiency exacerbates muscular dystrophy in MDX mice

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Introduction

Duchenne muscular dystrophy (DMD) is a fatal and incurable muscle degenerative disorder. We identify a function of the protease urokinase plasminogen activator (uPA) in mdx mice, a mouse model of DMD. The expression of uPA is induced in mdx dystrophic muscle, and the genetic loss of uPA in mdx mice exacerbated muscle dystrophy and reduced muscular function. Bone marrow (BM) transplantation experiments revealed a critical function for BM-derived uPA in mdx muscle repair via three mechanisms: (1) by promoting the infiltration of BM-derived inflammatory cells; (2) by preventing the excessive deposition of fibrin; and (3) by promoting myoblast migration. Interestingly, genetic loss of the uPA receptor in mdx mice did not exacerbate muscular dystrophy in mdx mice, suggesting that uPA exerts its effects independently of its receptor. These findings underscore the importance of uPA in muscular dystrophy.

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Abbreviations used in this paper: BM, bone marrow; CK, creatine kinase; CTX, cardiotoxin; DMD, Duchenne muscular dystrophy; HE, hematoxylin/eosin; HGF, hepatocyte growth factor; SC, satellite cell; SF, scatter factor; uPA, urokinase plasminogen activator; uPAR, uPA receptor; WT, wild type.

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injured muscles. Indeed, infiltrated inflammatory cells release several cytokines and growth factors that modulate muscle degeneration, inflammation, and regeneration (e.g., TNFα, VEGF, and nitric oxide synthase; Collins and Grounds, 2001; Wehling et al., 2001; Germani et al., 2003; Grounds and Torrisi, 2004; Chen et al., 2005, 2006; Tidball, 2005; Brunelli et al., 2007). We previously reported a critical role of the protease urokinase plasminogen activator (uPA) in the recovery of experimentally injured muscle (Lluis et al., 2001). Among the several enzymatic functions of uPA, the most classic one is the ability to convert the zymogen plasminogen into active plasmin, whose classic role is degradation of the fibrinogen end product fibrin (from here on, we refer to both by the term fibrinogen). By binding of uPA to its uPA receptor (uPAR), uPAR localizes the conversion of plasminogen to plasmin to the cell surface, thereby increasing pericellular proteolysis. In addition, uPAR also allows uPA to induce intracellular signaling, thereby promoting cell proliferation and migration (Blasi and Carmeliet, 2002; Mondino and Blasi, 2004). Importantly, uPA and plasmin promote inflammatory cell infiltration and repair of injured muscle, whereas the role of uPAR herein remains unclear (Lluis et al., 2001; Suelves et al., 2002). As the role of uPA and uPAR in mdx dystrophy remains unknown, we therefore intercrossed mdx mice with mice lacking either uPA (uPA−/−) or uPAR (uPAR−/−) and examined disease progression and its pathological features.

Results

Expression of uPA in mdx muscle dystrophy

We previously showed that uPA mediates the recovery of experimentally injured muscle (Lluis et al., 2001), but its role in mdx dystrophy remains unknown. Therefore, we first analyzed by zymography uPA activity in mdx muscle extracts before and after the onset of muscle degeneration. At 14 d of age (i.e., before disease onset), the activity levels of uPA were undetectable in wild-type (WT) mice and in mdx mice (unpublished data). In contrast, after disease onset (i.e., 30 d of age), the activity levels of uPA were increased in mdx muscle but not in WT muscle (Fig. 1). These changes were specific for uPA, as no lytic band corresponding to tPA (at 72 kD) was detected by zymography (Fig. 1). Thus, uPA activity is specifically increased in mdx dystrophic muscle during disease.

Figure 1. Increased activity of uPA in mdx muscle dystrophy. Zymographic analysis of WT, mdx, and uPA−/− muscles. Purified murine uPA (45 kD) and tPA (72 kD) were used as a control for activity (+).

Genetic loss of uPA exacerbates mdx dystrophic disease

To evaluate whether uPA would affect the disease course in mdx mice, we intercrossed mdx mice with uPA−/− mice and phenotyped uPA+/−/mdx (from here on referred to as mdx) and uPA−/−/mdx littermates. Both genotypes were healthy at birth and did not show any signs of muscle injury or differences in muscle size before disease onset (14 d of age; Fig. 2 a and d; and Table S1, available at http://www.jcb.org/cgi/content/full/jcb.200705127/DC1). Beyond 3–4 wk of age, obvious signs of muscle dystrophy were detectable in mdx and uPA+/−/mdx mice. However, compared with mdx mice, uPA+/−/mdx mice suffered from a much more severe dystrophinopathy, at least up to 4 mo of age, as characterized by a more widespread and extensive myofiber degeneration and necrosis (Fig. 2 a). Indeed, uPA+/−/mdx muscles contained larger areas of muscle damage and significantly more clusters of degenerated myofibers (P < 0.05; Fig. 2 b).

To ascertain worsening in the pathology of the whole skeletal musculature, we measured the serum levels of creatine kinase (CK), a biomarker of sarcolemmal damage (Butfield et al., 1984). Consistent with the more severe muscle degeneration, uPA+/−/mdx mice showed approximately twofold higher serum CK levels as compared with mdx mice at 2.5 mo of age (Fig. 2 f). To determine the functional status of the diseased muscle, we used grip-strength and treadmill assays. Compared with mdx mice, muscle strength at 2.5 mo of age was substantially decreased in uPA+/−/mdx mice in both assays (Fig. 2 g). Altogether, these findings provide histological, biochemical, and functional evidence that uPA deficiency aggravates muscle degeneration and attenuates regeneration in mdx muscle.

BM-derived uPA promotes the infiltration of inflammatory cells into mdx dystrophic muscle

In experimentally injured muscle, uPA is produced by SCs and by inflammatory cells (Lluis et al., 2001). Although T lymphocytes and neutrophils also infiltrate dystrophic mdx muscles, infiltrated macrophages appear to be the major inflammatory cell type (Fig. S1 a, available at http://www.jcb.org/cgi/content/full/jcb.200705127/DC1; Engel and Arahata, 1986; Pimorady-Esfahani et al., 1997; Spencer et al., 2001; Tidball, 2005). We first aimed to analyze the impact of uPA deficiency in the inflammatory response in mdx muscular dystrophy. Before disease onset (i.e., at 14 d of age), Mac-1+ macrophages and T-11+ T lymphocytes were rarely detected in mdx or uPA+/−/mdx muscles (Fig. 3 a). After disease onset (i.e., at 30 d of age), these inflammatory cells had infiltrated the dystrophic muscle of mdx mice (Fig. 3 a). However, compared with mdx mice, the number of infiltrated macrophages and T lymphocytes was significantly reduced in uPA+/−/mdx mice (Fig. 3 a).
Mac-1+ and T-11+ cells in uPA+/− mdx muscle was reduced up to ~50% (Fig. 3 a). Consistent with this, the loss of uPA also reduced the number of infiltrated inflammatory cells in cardiotoxin (CTX)-injured muscle (Fig. S2 a). This was not the result of a genotypic difference in the number of circulating leukocytes in the peripheral blood (unpublished data).

This reduced infiltration and accumulation of inflammatory cells in uPA+/− mdx dystrophic muscles was likely attributable to the fact that they lack the uPA needed to invade injured tissues. Indeed, when performing in vitro migration experiments, uPA+/− mdx and uPA−/− macrophages were found to migrate less compared with control cells (Figs. 3 b and S2 b). Therefore, we evaluated whether the conditional restoration of uPA expression in the bone marrow (BM) of uPA−/− mdx mice achieved via the transplantation of uPA+/−+/− mdx BM (termed uPA+/−+/− mdx(BM)-mice from here on) could revert the deficient inflammatory response. As a negative control, we transplanted uPA+/− mdx BM into uPA+/− mdx mice (uPA+/−+/− mdx(BM)-mice). We also transplanted WT BM into uPA−/− recipient mice (term uPA−/−(WT-BM) mice from here on) or into WT mice (WT(WT-BM) mice) and induced muscle injury by intramuscular injection of CTX (supplemental material, available at http://www.jcb.org/cgi/content/full/jcb.200705127/DC1). In both experiments, we found that the transplantation of uPA-expressing BM increased the infiltration of inflammatory cells into dystrophic or injured uPA-deficient muscles. Indeed, compared with uPA+/−+/− mdx(BM)-mice, muscles in uPA+/−+/− mdx(BM)-mice became infiltrated with plenty of (uPA expressing) inflammatory cells (Fig. 3 c); likewise, inflammatory cells accumulated in the damaged muscle in uPA+/−+/− mdx(WT-BM) mice to the levels found in WT or WT(WT-BM) mice (Fig. S2 c). Together, these data demonstrate that uPA is critical for inflammatory cells to infiltrate the degenerating myofibers of mdx mice.

BM-derived uPA attenuates the degeneration of mdx dystrophic muscle

There is increasing evidence that the inflammatory response can promote both muscle injury and repair (Tidball, 2005;
Arnold et al., 2007; Pelosi et al., 2007; Tidball and Wehling-Henricks, 2007). Therefore, we evaluated whether the transplantation of uPA-expressing BM also attenuated muscle degeneration in mdx mice. Compared with uPA−/−mdx(uPA−/−mdx-BM) mice, muscles in uPA−/−mdx(uPA−/−mdx-BM) mice exhibited less severe signs of degeneration at 2 mo after transplantation (Fig. 4 a). Consistent with this, serum CK levels were lower in uPA−/−mdx(uPA−/−mdx-BM) than in uPA−/−mdx(uPA−/−mdx-BM) mice (Fig. 4 b). Thus, uPA-expressing BM-derived cells attenuate muscle degeneration in uPA−/−mdx mice. Consistent with this notion, muscle damage was reduced and regeneration was rescued in uPA−/−mdx(WT-BM) mice at 10 d and 25 d after CTX injury, respectively, whereas degeneration persisted in nontransplanted uPA-deficient mice (Fig. 4 c).

Reduction of fibrin/ogen levels by BM-derived uPA or by ancrod treatment reduces the exacerbated degeneration of uPA−/−mdx mice

We previously showed that the persistent muscle degeneration in uPA−/− mice after injury was mediated, at least in part, by the impaired dissolution of intramuscular fibrin/ogen deposits (Lluis et al., 2001). Therefore, we analyzed in mdx and uPA−/−mdx muscle the extent of fibrin/ogen accumulation before and after disease onset. Before disease onset (14 d of age), fibrin/ogen was undetectable by immunostaining or Western blotting in mdx and uPA−/−mdx muscles (unpublished data). However, at the first disease peak (30 d of age), fibrin/ogen deposits were readily detectable in muscles of both genotypes (Fig. 5 a). Importantly, however, compared with mdx muscles, fibrin/ogen deposition was increased in uPA−/−mdx muscles up to 2.5-fold (Fig. 5 a). Interestingly, the prior transplantation of uPA-expressing BM cells attenuated this increased deposition of fibrin/ogen in uPA−/−mdx mice (Fig. 5 b) and in uPA−/− mice challenged with CTX (Fig. S2 d).

To directly prove that the increased accumulation of fibrin/ogen mediated the exacerbated dystrophic disease in uPA−/−mdx mice, we depleted the circulating fibrinogen levels by administering the defibrinogenating snake venom ancrod to uPA−/−mdx mice. Daily delivery of ancrod (1 U per day) starting at 12 d after birth and continuing for 18 d thereafter effectively reduced the accumulation of fibrinogen in uPA−/−mdx muscles (Fig. 5 c). Importantly, compared with saline, the area of degenerated muscle in uPA−/−mdx mice was significantly reduced (P < 0.05) by ancrod therapy, indicating that the increased deposition of fibrinogen mediated the severe muscle dystrophy in uPA−/−mdx mice (Fig. 5, d and e). In addition, compared with saline, fewer muscle groups containing >10 degenerating fibers were found in ancrod-treated uPA−/−mdx mice (Fig. 5 e). However, ancrod treatment in uPA−/−mdx mice failed to completely rescue the exacerbated muscle dystrophy phenotype of uPA−/−mdx mice. Indeed, compared with mdx mice, the muscle degeneration area was still larger in ancrod-treated uPA−/−mdx mice (compare Fig. 5 e with Fig. 2 b). This incomplete rescue might be attributable to the finding that inflammatory infiltration remained halted in
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BM cell-derived uPA promotes regeneration by stimulating muscle cell migration

To further study the role of uPA during muscle regeneration, we used the model of CTX-induced muscle injury, wherein regeneration can be analyzed in a more time-controlled fashion. Consistent with the mdx model, the loss of uPA impaired muscle regeneration in the CTX model (Fig. 4 c and supplemental material). Notably, transplantation of WT BM rescued the uPA−/− muscular dystrophy and rescues the regeneration defect in CTX-injured uPA−/− mice. (a and b) BM from mdx or uPA−/− mdx donor mice was transplanted into uPA−/− mdx mice, and different muscle parameters were analyzed at 2 mo after transplantation. (a) Histological analysis. (left) HE staining of muscle sections. (right) Reduced degeneration in uPA−/− mdx mice transplanted with BM from mdx donor mice. Percentage of total muscle-degenerating area. DG, degenerating group. (b) Reduced muscle damage in uPA−/− mdx mice transplanted with BM from mdx donor mice as reflected by decreased serum CK levels. (c) BM transplantation rescues the regeneration defect of uPA−/− mice. BM from WT mice was transplanted into uPA−/− mice (uPA−/−(WT-BM)) and into WT mice (WT(WT-BM)). At 6 wk after transplantation, muscle injury was induced by CTX injection in these mice as well as in aged-matched nontransplanted WT and uPA−/− mice. HE staining. Data are means ± SEM (error bars). n = 4 animals per group. *, P < 0.05. Bars, 50 μm.
regenerating myofibers (Figs. 2 and 4), we wondered whether uPA, which is expressed by SCs (Fig. S1 b; Lluis et al., 2001), might also affect SC functions. Activation and proliferation rates of SCs were comparable in \( \text{mdx} \) and \( \text{uPA}^{-/-}\text{mdx} \) muscles or in CTX-challenged WT and \( \text{uPA}^{-/-}\text{mdx} \) muscles (Fig. 6 a). Consistent with this, although uPA/plasmin mediates the activation of hepatocyte growth factor (HGF)/scatter factor (SF) and TGF-\( \beta \)1 (i.e., modulators of SC activation and proliferation; Naldini et al., 1992; Robertson et al., 1993; Odekon et al., 1994; Pimorady-Esfahani et al., 1997; Tatsumi et al., 1998; Yablonka-Reuveni et al., 1999; Shefer et al., 2001), the active levels of these factors were comparable in \( \text{mdx} \) and \( \text{uPA}^{-/-}\text{mdx} \) muscles or in WT and \( \text{uPA}^{-/-}\text{mdx} \) injured muscle (Fig. S3, available at http://www.jcb.org/cgi/content/full/jcb.200705127/DC1). Further-
more, SC–derived primary myoblasts from \( \text{uPA}^{-/-}\text{mdx} \) muscle showed normal proliferation and migration in vitro (Fig. 6, b–d). Interestingly, however, the addition of murine recombinant (r-uPA) stimulated the migration of WT and \( \text{uPA}^{-/-}\text{mdx} \) myoblasts in both scratch wounds and transwell assays (Fig. 6, c and d), although it failed to affect the proliferation rates (Fig. 6 b). Consistent with the promigratory effect of uPA, myoblast migration was increased in the presence of conditioned medium obtained from WT macrophage cultures (compared with nonconditioned control medium) but was only minimally stimulated by \( \text{uPA}^{-/-}\text{macrophage} \) conditioned medium (Fig. 6 e). The migration in response to WT macrophage conditioned medium was abrogated when the uPA inhibitor amiloride was added (Fig. 6 e). Moreover, the absence of migration in response to \( \text{uPA}^{-/-}\text{macrophage} \) conditioned medium was restored by supplementation with r-uPA (Fig. 6 e). Thus, our data suggest that macrophage-derived uPA might promote muscle regeneration by enhancing SC migration.

**Dispensability of uPAR for muscle regeneration after injury and in \( \text{mdx} \) dystrophinopathy**

By binding to uPAR, uPA is capable of exerting its proteolytic effects at the pericellular level, but it also enables uPA to...
promote cell proliferation and migration via nonproteolytic pathways (Blasi and Carmeliet, 2002; Mondino and Blasi, 2004). We found that uPAR expression was induced in muscle extracts of WT mice after CTX injury and of mdx mice after disease onset (Fig. 7 a). Thus, we reasoned that the role of uPA in muscle regeneration might be dependent, at least in part, on its binding to uPAR. To directly evaluate this hypothesis, we performed CTX injury in muscles of WT and uPAR-deficient mice (uPAR−/−), crossbred the mdx mice into the uPAR-deficient background (uPAR−/− mdx mice), and analyzed the consequences of uPAR deficiency on muscle regeneration in both models. CTX-induced muscle regeneration was indistinguishable between WT and uPAR−/− mice after histological analyses at 2, 10, and 25 d after injury (Fig. 7 b). Consistent with this,
the infiltration of inflammatory cells was also not affected in the absence of uPAR (Fig. 7 b). Most importantly, the muscle cross-sectional area and the extent of muscular dystrophy were also similar in mdx and uPAR−/−mdx mice (Fig. 7, c and d). Indeed, the percentage of muscle degeneration was not different between mdx and uPAR−/−mdx mice (Fig. 7 d). In addition, the number of infiltrated macrophages and T cells did not differ between mdx and uPAR−/−mdx mice (Fig. 7 c). Interestingly, the percentage of centrally nucleated fibers was slightly increased in uPAR−/−mdx mice (Fig. 7 d); however, SC–derived primary myoblasts from uPAR−/− mice presented normal proliferation and migration rates in vitro (Fig. S4, available at http://www.jcb.org/cgi/content/full/jcb.200705127/DC1).

Altogether, these results demonstrate that uPAR is dispensable for muscle tissue remodeling during regeneration both after acute injury and in mdx muscle dystrophy and suggest that uPA regulates key processes during muscle regeneration in a uPAR-independent manner.

Discussion

Despite intense research efforts, DMD is still an incurable and fatal disease. The principal finding of this study is that uPA plays an important reparative role in muscular dystrophy. Indeed, uPA expression and activity increase during dystrophic disease, and the genetic loss of uPA exacerbated muscle dystrophinopathy and worsened muscle performance in the mdx mouse model of Duchenne’s disease. Importantly, these defects in the absence of uPA were largely rescued by the transplantation of uPA-expressing BM, thus highlighting the importance of
uPA-secreting BM-derived cells in muscular dystrophy. Our data also indicated a critical role for fibrin/ogen deposits in dystrophic muscle and a crucial role for uPA to dissolve them. Notably, muscle dystrophinopathy was unaffected in the absence of uPAR, suggesting that uPA exerts its effect independently of its receptor. Thus, these results underscore the important role of muscle-extrinsic factors such as BM cell–derived uPA in DMD disease.

Our findings not only showed that uPA was produced by BM-derived cells but also that these cells required uPA for their infiltration into dystrophic muscle. Accordingly, macrophages showed reduced migration in vitro in the absence of uPA. It has long been proposed that inflammation exacerbates muscular dystrophy via the release of cytotoxic cytokines and free radicals, leading to myofiber necrosis (Spencer and Tidball, 2001; Grounds and Torrisi, 2004; Hodgetts et al., 2006; Pizza et al., 2005; Tidball, 2005), although recently, evidence has been accumulating on a positive role for inflammatory cells during muscle regeneration (Tidball, 2005; Sonnet et al., 2006; Arnold et al., 2007; Pelosi et al., 2007; Tidball and Wehling-Henricks, 2007). Indeed, we found less inflammation but increased muscle degeneration in uPA−/−mdx mice, whereas the transplantation of uPA-expressing inflammatory cells rescued these degenerative defects. Thus, it is conceivable that inflammatory cells require uPA to infiltrate degenerating muscles of dystrophic mice and initiate the repair process. Indeed, macrophages might require uPA for the activation and phagocytosis of necrotic debris and for extracellular matrix remodeling. It has been demonstrated that the activation and release of prerecovery cytokines by leukocytes is reduced in uPA−/− mice (Matsushima et al., 1986; Sitrin et al., 1996; Gyetko et al., 2002; Abraham et al., 2003) and that uPA−/− leukocytes have impaired phagocytosis capacity (Gyetko et al., 2004). One potential mechanism underlying the uPA-mediated activation of leukocytes might involve mac-tin, an α-actinin fragment that promotes monocyte/macrophage maturation, whose formation is mediated by uPA (Luikart et al., 2002; Luikart et al., 2006). Moreover, our data indicate that uPA-expressing inflammatory cells are required for intramuscular fibrinolysis. Collectively, we propose that uPA drives the infiltration and function of inflammatory cells required to create a beneficial environment for the repair of dystrophic muscle.

Another prerequisite for the efficient regeneration of dystrophic muscle appears to be prevention of the excessive deposition of fibrin/ogen. Indeed, in mdx muscle, fibrin/ogen accumulates as the disease progresses but is absent before disease onset. In the absence of uPA, both dystrophinopathy and fibrin/ogen accumulation were enhanced in mdx mice. Importantly, depletion of fibrinogen by ancrord treatment attenuated the severe muscle degeneration in uPA−/−mdx mice. Thus, removal of fibrin/ogen deposits appears to be required for the resolution of muscle damage in mdx mice. Unpublished findings indeed indicated that fibrin/ogen promoted the persistent inflammation and degeneration of mdx muscles. Thus, by preventing excessive fibrin/ogen accumulation, uPA produced by BM-derived inflammatory cells might attenuate muscle degeneration and persistent inflammation in mdx mice.

Several studies have shown that both uPA and uPAR are expressed by a variety of cells of hematopoietic origin (Plesner et al., 1997; Blasi and Carmeliet, 2002; Mondino and Blasi, 2004) and that both molecules are up-regulated during severe infections, supporting a role for the uPA–uPAR system in inflammatory responses. Indeed, in uPAR-deficient mice, macrophages and neutrophils failed to infiltrate the lungs of mice in response to microbial infections (Gyetko et al., 2000, 2001; Rijneveld et al., 2002) or to migrate to the inflamed peritoneum of thioglycollate-treated mice (May et al., 1998). Therefore, we reasoned that the critical role of uPA in driving the infiltration and function of inflammatory cells during mdx muscle regeneration might involve uPAR. However, our results clearly showed that the loss of uPAR did not affect the degeneration/regeneration process nor did it impair the inflammatory response in dystrophic muscle, indicating that uPA is not required for either process. Consistent with this notion, no degeneration or inflammatory phenotype was observed in uPAR-deficient mice after CTX injury. These results together with the reported observations that uPA and uPAR knockout mice have different susceptibilities to several pathogenic infections or biological processes (Carmeliet et al., 1998; Gyetko et al., 2000, 2001; Rijneveld et al., 2002; Deindl et al., 2003) indicate that uPAR and uPA may operate at different steps and may even be independent of each other.

After the clearance of degenerating myofibers by uPA+ inflammatory cells, muscle regeneration also appears to require uPA. Indeed, in the absence of uPA, muscle regeneration was attenuated in mdx and CTX-injured muscle; the transplantation of uPA-expressing BM rescued this defect. In addition, although the migratory capacity of primary myoblasts from uPA−/− muscle was normal, myoblast migration was enhanced in the presence of recombinant or macrophage-produced uPA. In contrast, the supplementation of r-uPA failed to affect their ability to proliferate. Thus, our results suggest that uPA derived from inflammatory cells specifically promotes the migration of muscle cells. As uPA deficiency failed to affect the activation of latent growth factors (e.g., HGF/SF or TGF-β1) in regenerating muscle in vivo, uPA might affect SC migration via alternative pathways. Unpublished findings from our group suggest that the removal of fibrin/ogen deposits promotes SC migration. Notably, these data extend previous observations that uPA promotes the migration of C2C12 immortalized myoblasts and primary human myoblasts by regulating membrane ruffling or by binding uPAR (Chazaud et al., 2000; Fibbi et al., 2001; El Fahime et al., 2002). However, we found that the genetic loss of uPAR did not affect primary myoblast migration.

DMD remains an incurable and fatal disease. No therapies correcting the primary defect in DMD (i.e., dystrophin replacement) are yet available, and current DMD therapies have a narrow therapeutic window (e.g., temporary efficacy and severe side effects). Our study shows that uPA activity, by providing an adequate inflammatory response and by promoting fibrinolysis and muscle regeneration, is beneficial in mdx muscle dystrophy. Notably, we and others recently demonstrated that genetic loss of the uPA inhibitor PAI-1 accelerated the recovery of CTX-injured muscle (Koh et al., 2005; Suelves et al., 2005). Thus, stimulating uPA activity may constitute a novel potential alternative for DMD disease amelioration.
Materials and methods

Generation of double mutant mice

uPA and uPAR knockout male mice (Carmeliet et al., 1994; Dewerchin et al., 1996) were crossed with mdx female mice (Jackson ImmunoResearch Laboratories). Male F1 mice were bred with mdx female mice, and their F2 heterozygous uPA and uPAR male and female offspring were intercrossed. The resulting F3 generation showed the expected Mendelian distribution of uPA−/−, uPAR−/−, mdx, uPA−/−/mdx, and uPAR−/−/mdx mice were removed after cervical dislocation, frozen, and stored at −80°C before analysis. 10 μm sections were collected from the midbelly of muscles and stained with hematoxylin/eosin (HE). Images were acquired with a microscope (DMR; Leica) equipped with a camera (DCB300 FX; Leica) and using 10× 0.25 NA, 20× 0.40 NA, and 40× 0.75 NA objectives (Leica). The acquisition software was the IM1000 program (Leica). The cross-sectional areas of entire muscles and myofibers were measured using the computer-assisted morphometric measurement Image 1.62c program (Scion).

Immunohistochemistry

The following primary antibodies were used for immunohistochemistry: anti–Mac-1 (M1/70; Hybridoma Bank), anti–I1 conjugated with fluorescein isothiocyanate (1:50; Coulter Immunology), anti–fibrinogen/–α(v)β3 (1:100; Nordic), anti-F4/80 (1:200; Serotec), and anti–uPA (1:20; Santa Cruz Biotechnology, Inc.). Depending on the antibody, immunohistochemistry was performed with the tyramide signal amplification cyanine 3 system (PerkinElmer) or as previously described (Luis et al., 2001; Suvelles et al., 2002). Control experiments with out–primary antibody demonstrated that the signals observed were specific.

Preparation of muscle extracts and Western blot analysis

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Zymography

Zymography of muscle extracts was performed as previously described (Luis et al., 2001). An SDS-PAGE gel was laid onto a casein gel, incubated in a humid chamber at 37°C until caseinolytic bands (corresponding to uPA or/and uPA) were visualized, and photographed.

Systemic defibrinogenation

12–old uPA−/−/mdx mice were daily injected intraoperatively with ancrd (1 U ancrd/day; Sigma-Aldrich) or with a saline solution for 18 d and killed at 30 d of age. Muscles were dissected and frozen before analysis.

Analysis of muscle fiber degeneration and regeneration

Muscle degeneration was determined microscopically and expressed as a percentage of the total muscle area. The number of DGs (degenerating groups) that contained >10 degenerating fibers was counted in complete muscle cross sections of mdx and uPA−/−/mdx mice. Muscle fiber regeneration was determined microscopically and expressed as the percentage of total muscle fibers containing central nuclei present in the entire cross section of the muscle.

Migration assays

Macrophage migration was assayed on transwells (3-μm pore size; Beckton Dickinson). BM-derived macrophages were obtained as previously described (Celada et al., 1984) from mdx and uPA−/−/mdx mice or from WT and uPA−/−/ mice. 5 × 104 macrophages/transwell in RPMI 1640 containing 1% FCS were added to the upper chamber of the transwell, and the conditioned medium of muscle SCSs, which was previously concentrated fivefold using the Centrifugal Filter Device (Millipore), was added to the lower chamber. SC migration was performed on 8-μm pore size transwells. SCSs from WT or uPA−/−/ mice (5 × 105 cells/transwell) in Hams F10 containing 1% FCS were added to the upper chamber of transwells. Transwells were coated with matrigel before addition of the cells. When indicated, 10 nM recombinant murine uPA (Molecular Innovations) was added to the lower chamber of the transwell. Alternatively, conditioned medium of WT or uPA−/−/ macrophages, which were previously concentrated 2.5-fold and supplemented or not supplemented with 10 nM of murine r-uPA (Molecular Innovations) or 1 mM amiloride (Sigma-Aldrich), was added to the lower chamber. After 16 h of incubation at 37°C, cells on the filter’s upper surface were scrapped off. Then, filters were fixed in cold ethanol and stained with 5% crystal violet. Cells on the filter’s lower surface were counted (12 fields per filter). Experiments were performed in triplicate.

Wound-healing assay in vitro

WT and uPA−/−/SCs (2 × 105 cells) were plated in 12-well plates coated with matrigel (BD Biosciences). Once cells were attached to the matrix, a wound was performed across the well using a sterile pipette tip with an outer diameter of 500 μm. When indicated, 10 nM recombinant murine uPA was added to the culture media. Cells were then photographed at 0, 8, and 24 h after wounding using a microscope with ×10 magnification (DMR; Leica). Experiments were performed in triplicate.

Induction of muscle regeneration

Regeneration of skeletal muscle was induced by intramuscular injection of 300 μl of 10−3 M CTX (Latoxan) in the gastrocnemius muscle group of the mice (Kherif et al., 1999). This concentration and volume were chosen to ensure maximum degeneration of the myofibers. The experiments were performed in right hindlimb muscles, and contralateral intact muscles were used as a control. Morphological and biochemical examinations were performed at 0, 2, 10, and 25 d after injury.

BM transplantation

Donor BM cells were obtained by flushing the femurs and tibiae of mdx or uPA−/−/mdx mice with RPMI 1640 medium (Invitrogen) and were transplanted into 4–old uPA−/−/mdx mice after lethal irradiation (9 Gy). Alternatively, donor BM cells were obtained from WT mice and transplanted into 8–old WT or uPA−/−/ mice. The reconstituting cells (5 × 105 cells) were injected intravenously into the tail of the recipient mice within 24 h after irradiation. Alternatively, donor BM cells were obtained from GFP mice (C57BL/6-GFPPLU-Saggy mice; provided by A. Nagy, Samuel Lunenfeld Research Institute, Mount Sinai Hospital, Toronto, Ontario, Canada) and were transplanted into 2–old WT and uPA−/−/ mice. The mice were placed in sterile cages and fed with sterile chow until the reconstitution of BM was completed 8 wk after the transplantation. No changes in general health status were noted in the recipient mice. Regeneration of skeletal muscle in WT and uPA−/−/ mice was induced by the intramuscular injection of CTX as described in the previous section.
SC isolation and FACS analysis of activated Scs

Scs were isolated from mdx and uPA−/− mice after 2.5 mo of age as described previously (Mitchell and Pavlath, 2004). For FACS analysis, 2 × 10^5 Scs were used. Scs were permeabilized with 70% EtOH for 1 h at −20°C after incubation with an anti-CD34 antibody (FITC anti–mouse CD34; Rat34; BD Biosciences). Next, Scs were incubated with an anti-MacD anti-body (MoD; Santa Cruz Biotechnology, inc.) followed by incubation with a phycoerythrin-labeled secondary antibody (donkey anti–rabbit phycocy- erythrin; Abcam). Activated Scs were cells double positive for CD34 and MoD. Experiments were performed in triplicate.

BrdU incorporation in vitro

WT, uPA−/−, and uPA−/−Scs were cultured in Ham’s F-10 medium containing 20% FBS. 3.5 × 10^5 cells were plated in 12-well plates. When indicated, recombinant murine uPA (Molecular Innovations) was added to the culture medium at different concentrations (2, 10, or 50 nM). After 18 h, proliferating cells were labeled with 1.53 μg/ml BrdU (Sigma-Aldrich) for 2 h. BrdU-labeled cells were detected by immunocytochemistry and counted microscopically. Antibodies used for immunodetection were mono-clonal rat anti-BrdU (1:200; Oxford Biotechnology) and biotin-SP-conjugated donkey anti–rat-IgG (1:250; Jackson ImmunoResearch Laboratories). Experiments were performed in triplicate.

BrdU incorporation in vivo

Gastrocnemius, quadriceps, and tibialis muscles from WT and uPA−/− mice were injected with CFT to induce muscle regeneration. 24 h after injury, 50 μg/kg BrdU was injected intraperitoneally. 18 h later, Scs were isolated as described previously (Mitchell and Pavlath, 2004) and cultured for 24 h in Ham’s F-10 medium containing 20% FBS. The percentage of Scs that had been BrdU labeled in vivo was determined by immunocytochemistry using a monoclonal rat anti-BrdU (as described above) and counted microscopically. Experiments were performed in triplicate.

RNA isolation and RT-PCR analysis

Total RNA was extracted from muscles or Scs using the commercially avail-able Ultraspec RNA isolation system (Biotecx). For RT-PCR, 2 μg of total RNA were reverse transcribed using the first-strand CDNA synthesis kit (GE Healthcare). Amplification parameters were denaturation at 94°C for 30 s, annealing for 30 s at 50°C (uPAR) and 55°C (uPA and glyceraldehyde-3-phosphate dehydrogenase), and extension at 72°C for 30 s. Primers for the detection of reverse transcriptase products were derived from different exons to distinguish RTPCR products from genomic DNA contaminations. Primer sequences were as follows: uPAR (5′-GTGACCTCAGGAGGACAGCAA-3′) and 5′-GCAGCTGCGTGGTGTGGTCACAACA-3′), uPA (5′-GGGAGTGATCTTGGAGCTCTCT-3′ and 5′-TAGAGGCTCTGGCCACACTG-3′), and glyceraldehyde-3-phosphate dehydrogenase (5′-ACTCCCACTCTCCACACCATCCTC-3′ and 5′-TCTTGAGCTCACTGCTTGC-3′). The expected product sizes were 140 bp, 450 bp, and 185 bp.

Measurement of activated HGF

Muscle extracts were analyzed for the presence of activated HGF by West-ern blotting using a goat anti–mouse IgG antibody (1:100; Santa Cruz Biotechnol-ogy, Inc.), which recognizes the active form (60 kD) of mouse HGF.

Measurement of activated TGF-β1

Crushed muscle extracts from mdx and uPA−/− mdx mice and from WT and uPA−/− mice after CTX injury were prepared as described previously (Chen and Quinn, 1992). The presence of activated TGF-β1 was analyzed using the QuantiKine TGF-β1 immunoassay kit (R&D Systems) according to the manufacturer’s instructions.

Statistical analysis

All quantitative data were analyzed by t test. P < 0.05 was considered statistically significant.

Online supplemental material

Table S1 shows a comparison of the morphometric properties of gastrocne-mius muscle of WT, mdx, and uPA−/− mdx mice. Fig. S1 demonstrates that macrophages and Scs express uPA. Fig. S2 shows that BM transplantation rescues abnormal inflammatory infiltration and fibrinogen deposition in uPA−/− mice. Fig. S3 shows that uPA-deficient muscles present normal activ-ated TGF-β1 and HGF/3F levels. Fig. S4 shows that uPA−/− Scs have normal proliferation and migration rates. Supplemental material contains a description of the impaired muscle regeneration in uPA-deficient mice after CTX injury. Online supplemental material is available at http://www.jcb.org/cgi/content/full/jcb.200705127/DC1.

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