Glucocorticoid-induced skeletal muscle atrophy is associated with upregulation of myostatin gene expression

Kun Ma,1,2 Con Mallidis,1 Shalender Bhasin,1 Vahid Mahabadi,1 Jorge Artaza,1,2 Nestor Gonzalez-Cadavid,1,2 Jose Arias,1 and Behrouz Salehian1

1Division of Endocrinology, Metabolism, and Molecular Medicine and 2Research Centers in Minority Institutions, Charles R. Drew University of Medicine and Science, Los Angeles, California 90059

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Ma, Kun, Con Mallidis, Shalender Bhasin, Vahid Mahabadi, Jorge Artaza, Nestor Gonzalez-Cadavid, Jose Arias, and Behrouz Salehian. Glucocorticoid-induced skeletal muscle atrophy is associated with upregulation of myostatin gene expression. Am J Physiol Endocrinol Metab 285: E363–E371, 2003. First published April 29, 2003; 10.1152/ajpendo.00487.2002.—The mechanisms by which excessive glucocorticoids cause muscular atrophy remain unclear. We previously demonstrated that dexamethasone increases the expression of myostatin, a negative regulator of skeletal muscle mass, in vitro. In the present study, we tested the hypothesis that dexamethasone-induced muscle loss is associated with increased myostatin expression in vivo. Daily administration (60, 600, 1,200 μg/kg body wt) of dexamethasone for 5 days resulted in rapid, dose-dependent loss of body weight (−4.0, −13.4, −17.2%, respectively, P < 0.05 for each comparison), and muscle atrophy (6.3, 15.0, 16.6% below controls, respectively). These changes were associated with dose-dependent, marked induction of intramuscular myostatin mRNA (66.3, 450, 527.6% increase above controls, P < 0.05 for each comparison) and protein expression (0.0, 260.5, 318.4% increase above controls, P < 0.05). We found that the effect of dexamethasone on body weight and muscle loss and upregulation of intramuscular myostatin expression was time dependent. When dexamethasone treatment (600 μg·kg−1·day−1) was extended from 5 to 10 days, the rate of body weight loss was markedly reduced to −2% within this extended period. The concentrations of intramuscular myosin heavy chain type II in dexamethasone-treated rats were significantly lower (−43% after 5-day treatment, −14% after 10-day treatment) than their respective corresponding controls. The intramuscular myostatin concentration in rats treated with dexamethasone for 10 days returned to basal level. Concurrent treatment with RU-486 blocked dexamethasone-induced myostatin expression and significantly attenuated body loss and muscle atrophy. We propose that dexamethasone-induced muscle loss is mediated, at least in part, by the upregulation of myostatin expression through a glucocorticoid receptor-mediated pathway.

GLUCOCORTICOIDS ARE COMMONLY USED in the treatment of a vast array of chronic inflammatory illnesses, such as systemic lupus erythematosus, sarcoidosis, rheumatoid arthritis, and bronchial asthma (3, 4, 7). However, administration of high doses of glucocorticoids causes muscular atrophy in humans and animals (8, 31). Similarly, hypercortisolism has a major role in muscular atrophy in Cushing’s disease (2, 33). Many previous studies have suggested that glucocorticoids inhibit protein synthesis and stimulate protein degradation in skeletal muscle (2, 38, 39, 41, 42). Although a number of mechanisms have been put forward to explain the action of glucocorticoids on skeletal muscle (15, 16, 29, 49), the precise molecular mechanisms by which glucocorticoids induce muscle atrophy are still not well understood.

Myostatin, formerly known as growth and differentiation factor 8, a member of the transforming growth factor-β superfamily, is an important negative regulator of skeletal muscle mass. Disrupted myostatin gene expression, either by gene targeting in mice or as a consequence of naturally occurring mutations in cattle, is associated with increased skeletal muscle mass resulting from muscle fiber hyperplasia as well as hypertrophy (17, 24, 25, 30, 32). Conversely, increased serum myostatin concentration is associated with a loss of skeletal muscle mass in men with the AIDS wasting syndrome (11). Increases in myostatin expression have also been reported in experimental animals after exposure to microgravity during space flight (22) and after hindlimb suspension (6, 48). We (44) and other investigators (45) have demonstrated that recombinant myostatin protein inhibits C2C12 muscle cell proliferation and protein synthesis in vitro. The mechanisms that regulate myostatin gene expression remain poorly understood.

To investigate the regulation of myostatin gene expression, we recently cloned and characterized the 5′-upstream regulatory region of the human myostatin gene and found that the promoter contains a number of response elements important for muscle growth, including seven putative glucocorticoid response elements (GREs). We also demonstrated that dexamethasone dose-dependently increases endogenous myostatin transcription in C2C12 myocytes through a glucocorticoid receptor-mediated mechanism (1, 26).
These findings led us to postulate that the increase in myostatin gene expression by glucocorticoids might contribute to the pathogenesis of glucocorticoid-induced skeletal muscle atrophy. In the present study, we tested this hypothesis in vivo in a rat model. First, we determined the effects of graded doses of dexamethasone on intramuscular myostatin gene expression. Second, we investigated the time course of dexamethasone effect on intramuscular myostatin gene expression. Finally, we examined whether the effects of dexamethasone on myostatin mRNA and protein can be reversed by concomitant administration of a glucocorticoid antagonist, RU-486.

MATERIALS AND METHODS

Animal care and experimental treatments. Male Sprague-Dawley rats, 10–12 wk of age, with initial body weights ranging from 250 to 420 g, were purchased from Harlan Laboratories. Each animal was housed individually in controlled environmental conditions (temperature 22°C, 12:12-h light-dark cycle period starting at 6:00 AM) and provided standard laboratory rodent chow and water. All experimental procedures on animals were approved by the Institutional Animal Care and Use Committee of the Charles R. Drew University of Medicine and were in accordance with National Institutes of Health guidelines for humane treatment of laboratory animals.

Study 1. We examined effects of different doses of dexamethasone administered intraperitoneally for 5 days on body weight, skeletal muscle weight, and intramuscular myostatin protein and mRNA expression. Sixty adult male rats were divided into six groups with even initial body weight distribution in each group. Three randomly selected groups, I, II, and III, received intraperitoneal injections of 1 ml of dexamethasone (Sigma) dissolved in saline (0.85% NaCl) at daily doses of 60, 600, and 1,200 μg/kg body wt, respectively. These doses were selected because administration of dexamethasone at 600 μg/kg body wt has been shown previously to cause muscle atrophy (12, 40). For each dose experiment, there was a control group also randomly chosen from the three groups. Thus each control animal, receiving a daily intraperitoneal injection of 1 ml of saline (vehicle, 0.85% NaCl) had a pair mate (matched by body weight) in the corresponding group receiving dexamethasone treatment. All dexamethasone-treated animals were allowed free access to food and water. Dexamethasone treatment has been reported to decrease food intake (40). It is not known whether food intake can affect myostatin expression independently in animals; therefore, each control animal was pair fed the same amount of food as was consumed by its dexamethasone-treated pair mate during the previous day.

Study 2. Forty rats were divided into four groups with equal total body weight distribution in each group. Two groups were randomly selected to receive dexamethasone treatment (600 μg/kg body wt) intraperitoneally daily for either 5 days (group I) or 10 days (group II), respectively. The 600 μg/kg body wt dose was selected because this dose resulted in significant loss of muscle mass in study 1. The remaining animals, used as controls, were randomly assigned to one of the two dexamethasone-treated groups. Each control animal, receiving daily intraperitoneal injection of vehicle (1 ml of 0.85% NaCl) had a pair mate (matched by body weight) in the corresponding dexamethasone-treated group. All dexamethasone-treated animals were allowed free access to food and water. Each control animal was allowed free access to water but pair fed the same amount of food as was consumed by its dexamethasone-treated pair mate during the previous day.

Study 3. We examined whether the glucocorticoid receptor antagonist RU-486 could inhibit the effect of dexamethasone on intramuscular myostatin protein and mRNA expression. In this experiment, 50 rats were divided into five groups with an even distribution of initial body weights in each group. The animals were randomly selected for receiving the following treatments for five consecutive days. Group Dex received dexamethasone (600 μg/kg body wt) daily; group Dex/RU-486 received dexamethasone (600 μg/kg body wt) and RU-486 (1,313 μg/kg body wt or 2× molarity of dexamethasone) daily; group RU-486 received RU-486 (1,313 μg/kg body wt) daily; control group PC was given daily saline injections and pair fed; and control group FC was given daily saline injections and free access to food. Animals in groups Dex and FC were allowed free access to the food and water, and their food intakes were recorded daily. Individuals in groups Dex/RU-486, RU-486, and PC were allowed free access to water but were pair fed with the same amount of food as was consumed by their dexamethasone-treated pair mates. In all studies, each individual’s body weight was recorded daily.

Muscle collection and calculation of change of muscle mass. After each experimental protocol, animals were killed by CO2 asphyxiation. The muscles of the gastrocnemius and flexor digitorum superficialis (G/FDS) complex from both legs were excised together, weighed on an analytical balance, and quickly frozen on dry ice and stored at −80°C for subsequent RNA and protein extractions. Although we tried to group animals with an even distribution of initial body weight, there were still minor differences in the averages of initial total body weights among experimental groups. Because the wet muscle weight can be measured only at the end of each experiment, we adjusted the average muscle weight of each experimental group by multiplying its measured average muscle weight (MW) by the ratio of its initial average body weight (BW) vs. that of the control group, i.e.

\[
\text{adjusted MW}_{\text{Group A}} = \frac{\text{measured MW}_{\text{Group A}}}{\text{BW}_{\text{control}}} \times \text{BW}_{\text{Group A}}
\]

Northern blot analysis. Total RNA was extracted from the G/FDS muscle complex with TRIzol (GIBCO-BRL), following the instructions provided by the manufacturer. The extracted RNA pellets were dissolved in diethyl pyrocarbonate-treated water. After the concentrations were determined by a spectrometer at 260 nm, all RNA samples were kept at −80°C until use. To determine the relative abundance of myostatin and the reference gene glyceraldehyde-3-phosphate dehydrogenase (GAPDH) mRNAs, 25 μg of heat-denatured total RNA for each muscle were electrophoresed (4 V/cm for 4 h) on a 1.8% agarose denaturing gel prepared in MOPS [40 mM sodium acetate, 1 mM EDTA, and 6.6% formaldehyde (all from Sigma)]. The RNA was transferred to a Hybond-XL nylon membrane (Amersham) by overnight capillary action in 20× SSC (3 M NaCl + 0.3 M Na2citrate, pH 7.0). Membranes were treated with ultraviolet cross-link (UV Stratalinker 1800; Strategene) at 70,000 μJ, as recommended by the manufacturer. Membranes that carried the RNA samples were first prehybridized in hybridization buffer (5× Denhardt’s, 6× SSC, 2.5% SDS, and 100 μg/ml denatured, sonicated salmon sperm DNA, 5 ml/100 cm2 filters) in hybridization bottles at 60°C for ≥2 h. DNA probes were radiolabeled by random priming with [α-32P]dCTP (ICN) with a High Prime kit (Roche), following the manufacturer’s instructions.
Statistical analysis. All data are reported as means ± SE. All statistical tests were performed using the Jandel SigmaStat statistical software package. *P < 0.05 is taken as the level of statistical significance. For study 1, the key outcome variables were body weight, weights of G/FDS complex, and myostatin protein and mRNA concentrations, corrected by GAPDH protein and mRNA. Treatment effects were analyzed by use of a two-way ANOVA model with factors for dose (60, 600, or 1,200 μg/kg body wt) and treatment (saline or dexamethasone). Comparisons between groups were performed with Tukey's test. For study 2, the data were analyzed by use of a two-way ANOVA model with factors for treatment (saline or dexamethasone) and treatment duration (5 or 10 days). Comparisons between groups were performed with the Tukey test. For study 3, the treatment effects in the five groups were analyzed with a one-way ANOVA model. Comparisons between groups were performed with Tukey's test.

RESULTS

Study 1: effects of 5-day dexamethasone treatment on body and muscle weight. Food intake decreased markedly in animals, particularly in the first 3 days after dexamethasone-treatment was initiated. The average food intakes of rats from each dexamethasone-treated group (60, 600, and 1,200 μg/kg body wt) on the day after the third dexamethasone injection were 19, 43, and 54% less than what they had eaten on the day before the dexamethasone treatment (data not shown).

Administration of dexamethasone caused a progressive, dose-dependent loss of body weight in rats (Table 1). The mean body weight reductions from baseline in dexamethasone-treated rats in groups I, II, and III (−4.0 ± 0.4, −13.4 ± 0.3, and −17.2 ± 0.4%, respectively) were significantly greater than those in the corresponding pair-fed controls (0.5 ± 0.4, −1.2 ± 0.3, and −4.5 ± 0.4%, respectively, P < 0.05; Table 1). The loss of body weight in pair-fed controls was apparently due to the restriction of their food intake.

The mean mass of the G/FDS complex was significantly lower in dexamethasone-treated rats than that in pair-fed controls within each dose group (Table 1). The rats treated with 600 and 1,200 μg/kg body wt daily had significantly lower muscle mass than those treated with the 60 μg/kg body wt (P < 0.05 for each comparison). As shown in Table 1, the losses of wet weight of G/FDS complex in dexamethasone-treated rats from groups I, II, and III were significantly (6.3 ± 0.4, 15.0 ± 0.3, and 16.6 ± 0.4%, respectively, all P < 0.05).
Dexamethasone treatment increases intramuscular myostatin gene expression. To determine whether dexamethasone administration affects myostatin expression in skeletal muscle from rats, we measured myostatin protein and mRNA concentrations in the G/FDS complex. The intramuscular myostatin mRNA concentrations, indicated by the abundance of a 2.9-kb transcript by Northern blot analysis, were significantly higher in dexamethasone-treated animals than in the corresponding pair-fed controls (P < 0.01). The dexamethasone-induced increase in intramuscular myostatin mRNA expression in rats was dose dependent. In rats that received five consecutive daily injections of dexamethasone at 60, 600, or 1,200 μg/kg body wt, the myostatin transcript and myostatin immunoreactive band detected in this study are consistent with the previously reported findings (6, 11, 48).

Study 2: time course of dexamethasone’s effects on body and muscle weight and intramuscular myostatin gene expression. To investigate whether extension of dexamethasone treatment would affect muscle weights and intramuscular myostatin protein and mRNA expression, we treated the rats with a daily injection of 600 μg/kg body wt dexamethasone for either 5 days (group I) or 10 days (group II). Again, dexamethasone administration induced a greater loss of body weight in both groups compared with their corresponding pair-fed controls. The average body weight changes in dexamethasone-treated rats from groups I and II, compared with their initial body weights, were −13.4 ± 0.6 (P < 0.05) and −15.3 ± 0.9% (P < 0.05), respectively. In contrast, the body weight changes of their corresponding pair-fed controls were −1.21 ± 1.0 and 0.42 ± 0.8%, respectively. However, the dexamethasone-induced changes in body weights between animals treated for 5 days and for 10 days were not significantly different from each other.

Overall, the average wet weights of G/FDS complex in dexamethasone-treated rats were 13.9 ± 0.71 and 16.5 ± 1.2% lower after 5 and 10 days of treatment compared with their pair-fed controls (P < 0.05 for each of the two comparisons). However, the wet weights of the G/FDS complex in rats treated with dexamethasone for 5 days (4.0 ± 0.2 g) were not significantly different from those in rats treated for 10 days (3.9 ± 0.3 g; Table 2). Interestingly, rats treated with dexamethasone for 5 days showed a marked de-
increased by 42.6% ($P < 0.05$) in the concentration of MHC II(A, X, B) isoforms in the G/FDS complex compared with the pair-fed controls. However, the concentration of MHC II(A, X, B) isoforms in animals treated with dexamethasone for 10 days was only 14.0% ($P < 0.05$) lower than that in the pair-fed controls (Fig. 2). No significant change was detected for MHC I in either dexamethasone-treated group.

As expected, the intramuscular myostatin mRNA expression in rats treated with dexamethasone for 5 days was (densitometry intensity reading 32.3 ± 1.5) significantly (4.50-fold, $P < 0.01$) higher than that in their pair-fed controls (densitometry intensity reading 5.9 ± 1.4) in their pair-fed controls. The myostatin protein expression in these rats was (densitometry intensity reading 19.2 ± 1.0; Fig. 3). However, after 10 days of treatment, intramuscular myostatin protein concentrations were not significantly different between the control and dexamethasone-treated rats (6.3 ± 1.5 vs. 5.8 ± 1.5, $P = 0.82$ for mRNA and 6.0 ± 1.1 vs. 5.7 ± 1.0, $P = 0.86$ for protein; Fig. 3).

**Study 3: RU-486 inhibits dexamethasone's effect on body weight and muscle weights and myostatin gene expression.** RU-486 is known to antagonize the effects of glucocorticoids by binding to the glucocorticoid receptors (20, 21, 28). To determine whether RU-486 antagonizes the effects of dexamethasone on myostatin mRNA and protein expression in vivo, we divided rats into five groups of equal body weight distribution. Three randomly selected groups were treated with dexamethasone (600 μg/kg body wt), dexamethasone (600 μg/kg body wt) plus RU-486 (1,313 μg/kg body wt), or RU-486 (1,313 μg/kg body wt) alone, respectively, for 5 days. To determine whether restriction of food intake could influence myostatin expression, we set up two groups of animals as controls, the pair-fed control (PC) and the free-access-to-food control (FC). Animals from both groups were given daily intraperitoneal injections of the vehicle (0.85% NaCl). The animals were killed after five consecutive daily treatments. Changes in their body weight, G/FDS mass, and myostatin gene expression were analyzed.

As shown in Table 3, animals in the FC group gained on average 7.8 ± 0.2% in body weight ($P < 0.05$) compared with their initial body weight, whereas the PC group lost 1.2 ± 0.3% ($P < 0.05$) in body weight. Dexamethasone-treated rats showed a much greater loss in body weight (-13.4 ± 0.3%, $P < 0.05$) compared with the PC group. Interestingly, Dex/RU-486 animals had significantly fewer losses in body weight (-6.4 ± 0.25%, $P < 0.05$) than those treated with dexamethasone alone, even though both groups of rats were fed the same amount of food. The change of body weight in the RU-486 group showed no significant difference from that in the PC group (Table 3).

The changes of body weights in the animals were mirrored by the wet muscle weights of each corresponding group. The average wet weight of G/FDS complex of the dexamethasone-treated rats (3.8 ± 0.1 g) was significantly lower than those of groups FC (4.9 ± 0.1 g, $P < 0.05$), PC (4.5 ± 0.1 g, $P < 0.05$), Dex/RU-486 (4.1 ± 0.1 g, $P < 0.05$), and RU-486 (4.5 ± 0.2, $P < 0.05$), respectively. There was no significant difference between the weights of wet G/FDS complex in the PC rats and in those treated with RU-486 alone (Table 3).

To determine whether RU-486 could alter the dexamethasone-induced increase in intramuscular myostatin expression in animals, we examined the mRNA and protein expression in the G/FDS complex from these

### Table 2. Dexamethasone time course effects on body weight and weight and wet muscle mass

<table>
<thead>
<tr>
<th>Group (n)</th>
<th>Treatment, days</th>
<th>Body Weight</th>
<th>Changes, %</th>
<th>G/FDS Weight, g</th>
<th>Dex-Induced G/FDS Weight Changes, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>C(5)</td>
<td>335.8 ± 14.0</td>
<td>331.7 ± 12.3</td>
<td>-1.21 ± 0.6</td>
<td>4.61 ± 0.2</td>
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<tr>
<td>(2 × 10)</td>
<td>Dex(5)</td>
<td>339.4 ± 14.9</td>
<td>293.9 ± 12.8</td>
<td>-13.4 ± 0.7*</td>
<td>3.93 ± 0.3*</td>
</tr>
<tr>
<td>II</td>
<td>C(10)</td>
<td>336.2 ± 14.2</td>
<td>337.6 ± 13.1</td>
<td>0.42 ± 0.8</td>
<td>4.67 ± 0.3</td>
</tr>
<tr>
<td>(2 × 10)</td>
<td>Dex(10)</td>
<td>338.7 ± 14.7</td>
<td>287.3 ± 12.3</td>
<td>-15.2 ± 0.9*</td>
<td>3.90 ± 0.3*</td>
</tr>
</tbody>
</table>

Values are expressed as means ± SE. *Dex at 600 μg per kg body wt daily; † adjusted value (see MATERIALS AND METHODS). Statistical analysis was carried out by 2-way ANOVA and Tukey's test. *Significantly different from corresponding pair-fed group ($P < 0.05$).

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**Fig. 2. Dexamethasone time effect on myosin heavy chain (MHC) in rats treated for 5 and 10 days. Top: MHC expression in G/FDS complex. Bottom: MHC II (quantified as OD). Sample loadings were adjusted by the OD of GAPDH. AU, arbitrary units. *P < 0.05, significantly different from the corresponding pair-fed control (600 μg·kg⁻¹·day⁻¹).**

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animals by using Northern and Western blot analyses. As displayed in Fig. 4, we found no significant difference in the intramuscular myostatin mRNA expression among animals from Groups FC, PC, and RU-486 (densitometry intensity readings 5.9 ± 0.9, 5.8 ± 0.9, and 5.6 ± 1.0, respectively, P < 0.05). The intramuscular myostatin mRNA expressions were 4.5-fold higher in dexamethasone-treated rats compared with their pair-fed controls (densitometry intensity reading 32.3 ± 1.6 vs. 5.8 ± 0.2, P < 0.05). The action of dexamethasone treatment on myostatin mRNA expression was effectively nullified by RU-486 administration, as the intramuscular myostatin mRNA expression in Dex/RU-486 rats (densitometry intensity reading 6.4 ± 1.0, P < 0.05) showed no significant difference compared with that in groups PC or FC (Fig. 4A).

Similarly, there was no significant difference in the intramuscular myostatin protein expression among animals from the FC, PC, and RU-486 groups (densitometry intensity readings 5.3 ± 0.3, 5.3 ± 0.2, and 5.2 ± 0.2, P < 0.05). The intramuscular myostatin protein expression in the dexamethasone-treated rats (densitometry intensity reading 19.2 ± 1.4, P < 0.01) was significantly higher than those in groups PC (5.3 ± 0.2, P < 0.05), PC (5.3 ± 0.2, P < 0.05), and RU-486 (5.2 ± 0.2, P < 0.05). Again, the dexamethasone-induced increase in myostatin protein expression was completely blocked by RU-486, because the myostatin protein expression (densitometry intensity reading 5.4 ± 0.3, P < 0.05) in animals concurrently administered dexamethasone plus RU-486 showed no significant difference from that in the PC group (Fig. 4B).

Table 3. Effects of dexamethasone plus RU-486 on body weight and wet muscle mass

<table>
<thead>
<tr>
<th>Treatment Group (n)</th>
<th>Body Weight</th>
<th>Dex-Induced G/PDS Weight Changes, %</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Initial, g</td>
<td>Final, g</td>
</tr>
<tr>
<td>FC(10)</td>
<td>329.7 ± 16.3</td>
<td>355.5 ± 16.6</td>
</tr>
<tr>
<td>PC(10)</td>
<td>332.1 ± 17.7</td>
<td>328.2 ± 16.1</td>
</tr>
<tr>
<td>Dex(10)</td>
<td>325.2 ± 18.5</td>
<td>251.6 ± 17.2</td>
</tr>
<tr>
<td>Dex/RU-486(10)</td>
<td>326.2 ± 15.3</td>
<td>305.3 ± 17.1</td>
</tr>
<tr>
<td>RU-486(10)</td>
<td>328.0 ± 14.7</td>
<td>324.4 ± 14.4</td>
</tr>
</tbody>
</table>

Values are expressed as means ± SE. FC, controls with free access to food; PC, pair-fed control; Dex/RU-486, Dex plus RU-486. *Dex at 600 µg per kg body weight daily; badjusted value (see MATERIALS AND METHODS). *RU-486 at 1,313 µg per kg body weight daily. Statistical analysis was carried out by 1-way ANOVA and Tukey’s test. *Significantly different from corresponding pair-fed group (P < 0.05).
DISCUSSION

Our study, although confirming previous observations that dexamethasone treatment leads to a dose-dependent loss of total body weight and skeletal muscle mass (2, 38, 39, 41, 42), is the first to demonstrate that this loss is associated with a dose-dependent upregulation of intramuscular myostatin mRNA and protein expression in vivo. These increases in intramuscular myostatin protein and mRNA concentrations were pronounced after 5 days of the treatment; however, the hyperexpression was not sustained, in either myostatin mRNA or protein expression, when treatment was extended to 10 days. Coinciding with the changes in myostatin expression, a marked decrease was found in MHC II protein expression. This decline of MHC expression was particularly obvious on day 5 of treatment, when myostatin expression was at its peak.

Unlike myostatin, the decline in MHC II expression was maintained after 10 days of treatment, albeit at a decreased rate (14% compared with the 42.6% after 5 days). The addition of the potent glucocorticoid receptor antagonist RU-486 reversed the dexamethasone-induced hyperexpression of intramuscular myostatin, suggesting that the glucocorticoid’s influence on myostatin expression may be mediated through glucocorticoid receptor-mediated mechanisms.

Because loss of body weight during dexamethasone administration is largely attributed to skeletal muscle atrophy (10, 12, 39, 41), it was not surprising that the reduction in total body weight found in our dexamethasone-treated rats was proportionately less than the associated loss of G/FDS mass. The mechanism(s) by which glucocorticoids induce such catabolic and anti-anabolic effects on muscle remains unclear. Previous studies have shown that glucocorticoids promote protein degradation and impair protein synthesis, which result in muscle atrophy (2, 10, 12, 39, 41); however, the precise molecular mechanisms of these actions are yet to be elucidated.

A large body of emerging data suggests that myostatin is an important negative regulator of skeletal muscle mass (11, 17, 30, 32, 36, 37, 44, 45). Disruption of myostatin gene expression is associated with dramatic increases in skeletal muscle mass due to muscle fiber hyperplasia and/or hypertrophy (13, 17, 30, 32). Conversely, increased myostatin levels are associated with loss of skeletal muscle mass in conditions as disparate as AIDS wasting syndrome (11), exposure to microgravity during space flight (22), and hindlimb suspension (6, 48). Glucocorticoid-induced protein degradation resulting in muscle atrophy is known to occur predominantly in fast-twitch muscle fibers (MHC IIB), (9, 39, 47). Interestingly, myostatin gene expression appears to be much higher in muscles (e.g., G/FDS complex and extensor digitorum longus), which are mainly composed of fast-twitch fibers, than in those composed of slow-twitch fibers (e.g., soleus) (6, 18, 48). Our previous in vitro observations that recombinant myostatin protein inhibits muscle cell proliferation and protein synthesis (36, 37, 44, 45) suggest that it may have an antianabolic effect.

Previously, we identified multiple putative GREs in the human myostatin gene (26) and demonstrated that, in vitro, dexamethasone dose-dependently upregulated endogenous myostatin mRNA and protein expression by increasing myostatin gene transcription
Our present in vivo observation emulates the previous finding (i.e., dexamethasone treatment resulted in significant dose-dependent increase in myostatin expression and a rapid decline of G/FDS mass), suggesting that dexamethasone-induced muscle atrophy is also associated with the upregulation of myostatin expression.

RU-486 inhibits glucocorticoid receptor binding and thus prevents dexamethasone-induced muscle atrophy (14, 20, 46). In the present study, dexamethasone’s effects on skeletal muscle mass and myostatin protein and mRNA concentrations were antagonized by concurrent treatment with RU-486. This suggests that dexamethasone affects myostatin expression predominantly through a glucocorticoid receptor pathway. Although dexamethasone affects myostatin mRNA and protein expression, it has been reported previously (14, 20, 46). Our present in vivo observation emulates the previous finding (1, 26). Our present in vivo observation emulates the previous finding (1, 26).

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