Atomoxetine Prevents Dexamethasone-Induced Skeletal Muscle Atrophy in Mice

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Received June 9, 2014; accepted October 6, 2014

ABSTRACT

Skeletal muscle atrophy remains a clinical problem in numerous pathologic conditions. β2-Adrenergic receptor agonists, such as formoterol, can induce mitochondrial biogenesis (MB) to prevent such atrophy. Additionally, atomoxetine, an FDA-approved nor-epinephrine reuptake inhibitor, is positive in a cellular assay for MB. We used a mouse model of dexamethasone-induced skeletal muscle atrophy to investigate the potential role of atomoxetine and formoterol to prevent muscle mass loss. Mice were administered dexamethasone once daily in the presence or absence of formoterol (0.3 mg/kg), atomoxetine (0.1 mg/kg), or sterile saline. Animals were euthanized at 8, 16, and 24 hours or 8 days later. Gastrocnemius muscle weights, changes in mRNA and protein expression of peroxisome proliferator–activated receptor-γ coactivator-1α (PGC-1α) isoforms, ATP synthase β, cytochrome c oxidase subunit I, NADH dehydrogenase (ubiquinone) 1 β subcomplex, 8, ND1, insulin-like growth factor 1 (IGF-1), myostatin, muscle Ring-finger protein-1 (muscle atrophy), phosphorylated forkhead box protein O 3a (p-FoxO3a), Akt, mammalian target of rapamycin (mTOR), and ribosomal protein S6 (rp-S6; muscle hypertrophy) in naive and muscle-atrophied mice were measured. Atomoxetine increased p-mTOR 24 hours after treatment in naive mice, but did not change any other biomarkers. Formoterol robustly activated the PGC-1α-4-IGF1–Akt–mTOR–rp-S6 pathway and increased p-FoxO3a as early as 8 hours and repressed myostatin at 16 hours. In contrast to what was observed with acute treatment, chronic treatment (7 days) with atomoxetine increased p-Akt and p-FoxO3a, and sustained PGC-1α expression and mitochondrial muscle mass in dexamethasone-treated mice, in a manner comparable to formoterol. In conclusion, chronic treatment with a low dose of atomoxetine prevented dexamethasone-induced skeletal muscle wasting and supports a potential role in preventing muscle atrophy.

S.R.J. and M.C.K. contributed equally to this work.

This work was supported by the National Institutes of Health National Institute of General Medical Sciences [Grant R01-GM084147]; the National Institutes of Health National Center for Research Resources [Grant UL1-RR029882]; the Biomedical Laboratory Research and Development Program of the Department of Veterans Affairs [BX-000851]; an SC COBRE in Oxidants, Redox Balance, and Stress Signaling [P20 GM105542-02]; and the South Carolina Clinical and Translational Research Institute, which has an academic home at the Medical University of South Carolina. Animal facilities were funded by National Institutes of Health National Center for Research Resources [Grant C06-RR015453].

dx.doi.org/10.1124/jpet.114.217380.

AABBREVIATIONS: ADHD, attention deficit hyperactivity disorder; β2-AR, β2-adrenergic receptor; EX2, exon 2; FoxO3a, forkhead box protein O 3a; IGF-1, insulin-like growth factor 1; MB, mitochondrial biogenesis; mTOR, mammalian target of rapamycin; MuRF-1, muscle RING-finger protein-1; MYSTN, myostatin; NDUF8B, NADH dehydrogenase (ubiquinone) 1 β subcomplex, 8; NRF, norpinephrine reuptake inhibitor; PGC-1α, peroxisome proliferator–activated receptor-γ coactivator-1α; qPCR, quantitative real-time polymerase chain reaction; rp-S6, ribosomal protein S6.
gene-1, and muscle RING-finger protein-1 (MuRF-1) (McPherron et al., 1997; Bodine et al., 2001; Gomes et al., 2001; Lee, 2004; Sacheck et al., 2007; Bonaldo and Sandri, 2013). High-dose glucocorticoid treatment (e.g., dexamethasone) is a standard animal model of skeletal muscle atrophy. Dexamethasone is thought to induce atrophy, in part, by indirectly preventing the activation of FoxO3a and MuRF-1 (Qin et al., 2010; Bonaldo and Sandri, 2013; Schiaffino et al., 2013).

In contrast, skeletal muscle growth is regulated by the insulin-like growth factor 1 (IGF-1)-Akt-mammalian target of rapamycin (IGF-1–Akt-mTOR) pathway (Musaro et al., 2001; Adams, 2002a,b; Schiaffino et al., 2013). Akt stimulates protein synthesis by activating mTOR and its downstream effector ribosomal protein S6 (rp-S6) (Adams, 2002b; Bonaldo and Sandri, 2013; Schiaffino et al., 2013). In addition, Akt can prevent muscle protein degradation by phosphorylating FoxO3a to prevent nuclear translocation and activation of MuRF-1 (Sandri et al., 2004; Senf et al., 2010).

In vivo and in vitro models have established a role for peroxisome proliferator-activated receptor-γ coactivator-1α (PGC-1α) in preventing muscle wasting (Bonaldo and Sandri, 2013). PGC-1α is a transcriptional coactivator that regulates the transcription of genes that drive mitochondrial biogenesis (MB) (Wu et al., 1999). Recently, alternative splice variants of the PGC-1α gene have been identified (Ruas et al., 2012). Each of the individual PGC-1α isoforms regulates a discrete gene

![Fig. 1. PGC-1α isoform gene expression in skeletal muscle of naive mice after formoterol or atomoxetine treatment. Naive mice were given a single dose of either formoterol (0.3 mg/kg i.p.), atomoxetine (0.1 mg/kg i.p.), or sterile saline (veh i.p.) and euthanized at 8, 16, and 24 hours. Gastrocnemius muscle was excised from animals at each time point and RNA was isolated for qPCR analysis. Total PGC1α (EX2), PGC1α1, and PGC1-1α4 at 0, 8, 16, and 24 hours after treatment with formoterol (A–C) or atomoxetine (D–F). Data were normalized to vehicle and represented as a relative fold-change. Data are expressed as means ± S.E. (n = 5). *Significantly different from untreated mice (P ≤ 0.05).](image-url)
program. For example, the induction of the PGC-1α isoform promotes MB and regulates mitochondrial oxidative phosphorylation gene expression (Mootha et al., 2004; Schreiber et al., 2004). Interestingly, PGC-1α1 has also been reported as preventing muscle atrophy by negatively regulating expression of MuRF-1, preventing active nuclear forms of FoxO from binding to the MuRF-1 promoter region (Sandri et al., 2006; Brault et al., 2010; Qin et al., 2010). Treatment with high-dose dexamethasone has been reported to reduce total PGC-1α protein expression and increase transcription of the MuRF-1 atrogate (Qin et al., 2010). In contrast, the PGC-1α4 isoform specifically activates IGF-1 expression and represses myostatin, which was shown to increase muscle mass, strength, and resistance to muscle wasting in a model of cancer cachexia (Ruas et al., 2012).

The benefits of therapeutic intervention with β2-adrenergic receptor (β2-AR) agonists in animal models of muscle atrophy have been previously established (Sato et al., 2011). β2-AR agonists, such as clenbuterol and formoterol, are considered progrowth and antiatrophic drugs (Kline et al., 2007). Formoterol induces skeletal muscle hypertrophy through activation of the Akt-mTOR-rp-S6 pathway and prevention of protein degradation (Joassard et al., 2013a). However, chronic administration of high doses of β2-AR agonists have been documented as causing adverse cardiovascular effects (Sato et al., 2011). Therefore, drugs that can prevent muscle atrophy in the absence of adverse cardiovascular effects are needed.

Atomoxetine (or tomatoxetine) is an FDA-approved drug to treat attention deficit hyperactivity disorder (ADHD) by preventing the neuronal reuptake of norepinephrine (Bymaster et al., 2002). A recent screen to discover compounds that promote MB identified atomoxetine and β-adrenergic receptor agonists as potent inducers of MB (Peterson et al., 2013). Given the previously established links between MB-associated pathways and the prevention of muscle atrophy, we sought to evaluate the role atomoxetine in preventing dexamethasone-induced skeletal muscle atrophy and to identify associated signaling pathways. Efficacy and signaling mechanisms were compared with formoterol, which is well characterized and has previously been used in this model.

Materials and Methods

Animals and Treatments

Male C57BL/6 mice (The Jackson Laboratories, Bar Harbor ME), 6–8 weeks of age (25–30 g), were housed in temperature-controlled conditions under a light/dark photocycle with food and water supplied ad libitum.

Acute Treatment Details. Groups of naive mice were injected intraperitoneally with a single dose of sterile saline, 0.3 mg/kg of formoterol fumarate dihydrate (Sigma-Aldrich, St. Louis, MO) or 0.1 mg/kg atomoxetine (Tocris Bioscience, Bristol, UK). Animals were euthanized at 8, 16, and 24 hours after treatments.

Dexamethasone-Induced Muscle Atrophy Model. One group of mice was coinjected intraperitoneally with sterile saline daily for 7 days.

Fig. 2. IGF-1 and myostatin gene expression in skeletal muscle of naive mice after formoterol or atomoxetine treatment. Mice were treated as described in Fig. 1. Expression of IGF-1 and myostatin at 0, 8, 16, and 24 hours after treatment with formoterol (A and B) or atomoxetine (C and D). Data were normalized to vehicle and represented as a relative fold-change. Data are expressed as means ± S.E. (n = 5). *Significantly different from untreated mice (P ≤ 0.05).
Three groups of mice were coinjected intraperitoneally with 25 mg/kg water-soluble dexamethasone (Sigma-Aldrich) followed by a second injection of sterile saline, 0.3 mg/kg of formoterol, or 0.1 mg/kg atomoxetine, respectively, daily for 7 days. Animals were euthanized on the 8th day.

Body weights were measured and gastrocnemius muscles were removed, weighed, and flash-frozen for mRNA and protein analysis. All animal and treatment protocols were in compliance with the Guide for Care and Use of Laboratory Animals as adopted and promulgated by the US National Institutes of Health and were approved by our Institutional Animal Care and Use Committee.

**Quantitative Real-Time Polymerase Chain Reaction**

Total RNA was extracted from mouse gastrocnemius tissue samples using TRIzol reagent (Invitrogen, Grand Island, NY) according to the manufacturer’s protocol. cDNA was synthesized via reverse transcription using the iScript Advanced cDNA Synthesis Kit (Bio-Rad, Hercules, CA) with 5 μg of RNA. Quantitative real-time polymerase chain reaction (qPCR) analysis was performed with cDNA and carried out using 5 μl of cDNA template combined with Brilliant II SYBR Green master mix (Stratagene/Agilent Technologies, La Jolla, CA) at a final concentration of 1/2°C and primers (Integrated DNA Technologies, Inc., Coralville, IA) at a concentration of 400 nM. mRNA expression of all genes was calculated using the 2-ΔΔCT method normalized to β-actin. Primer sequences are as follows:

- **Total PGC-1α (EX2)** (FW: 5'-TGA TGT GAA TGA CTT GGA TAC AGA CA-3', REV: 5'-GCT CAT TGT TGT ACT GGT TGG ATA TG-3'),
- **PGC-1α1** (FW: 5'-GGA CAT GTG CAG CCA AGA CTC T-3', REV: 5'-CAC TTC AAT CCA CCC AGA AAG CT-3'),
- **PGC-1α4** (FW: 5'-TCA CAC CAA ACC CAC AGA AA-3', REV: 5'-CTG GAA GAT ATG GCA CAT-3'),
- **Myostatin** (FW: 5'-AGT GGA TCT AAA TGA GGG CAG T-3', REV: 5'-GTT TCC AGG CGC AGC TTA-3'),
- **IGF-1** (FW: 5'-TGC TCT TCA GTT CTT GGT G-3', REV: 5'-ACA TCT CCA GTC TCC TCA G-3'),
- **β-Actin** (FW: 5'-GGG ATG TTT GCT CCA ACC AA-3', REV: 5'-GCC CTT TTG ACT CAG GAT TTA-3').

**Mitochondrial DNA Content**

qPCR was used to measure the relative quantity of mtDNA in mouse gastrocnemius tissue samples. After treatment, DNA was extracted from tissue using the DNeasy Blood and Tissue Kit (Qiagen, Valencia, CA) and 5 ng of DNA was used for qPCR. ND1 (FW: 5'-TAG AAC GCA AAA TCT TAG GG-3', REV: 5'-TGC TAG TGT GAG TGA TAG GG-3') was used as the mitochondrial gene, and expression was normalized to nuclear-encoded β-actin expression.

**Immunoblot Analysis**

Mouse gastrocnemius skeletal muscle tissue was homogenized in 5 volumes of protein lysis buffer (1% Triton X-100, 150 mM NaCl, 10 mM Tris, 150 mM NaCl, 1% Triton X-100). Samples were incubated on ice for 30 minutes and centrifuged at 13000 g for 15 minutes at 4°C. Protein concentrations were determined using a BCA Protein Assay Kit (Thermo Fisher Scientific, Waltham, MA).

**Fig. 3.** Acute effects of atomoxetine and formoterol on protein synthesis signaling mechanisms in skeletal muscle of naive mice. Mice were treated as described in Fig. 1. Representative immunoblots for markers of muscle protein homeostasis: total and phosphorylated forms of Akt-mTOR-rp-S6 axis and FoxO3a at 0, 8, and 24 hours after either formoterol (A) or atomoxetine (F). Densitometric analysis of FoxO3a (B), Akt (C), mTOR (D), and rp-S6 (E) ± formoterol; densitometric analysis of FoxO3a (G), Akt (H), mTOR (I), and rp-S6 (J) ± atomoxetine. Data were normalized to vehicle and represented as relative fold-change. Data are expressed as means ± S.E. (n = 4). *Significantly different from untreated mice (P ≤ 0.05).
Acute Treatment with Formoterol, but Not Atomoxetine, Differentially Modulates PGC-1α Isoform Expression in Skeletal Muscle of Naive Mice. PGC-1α has been described as a "master regulator" of MB (Pearen et al., 2008, 2009; Wills et al., 2012). In contrast, PGC-1α4, a recently discovered PGC-1α splice variant, induces a discrete gene program resulting in muscle hypertrophy but not MB (Ruas et al., 2012). It is important to note that all variants of the PGC-1α gene identified by Ruas et al. (2012) contain the exon 2 (EX2) region. Therefore, primer sequences that contain this region measure total PGC-1α expression (all isoforms). Because identification of the specific PGC-1α isoform induced by formoterol or atomoxetine has not been identified, we evaluated the effects of acute formoterol or atomoxetine treatment on PGC-1α isoform mRNA in skeletal muscle of naive mice.

Formoterol caused a 12-fold induction of total PGC-1α (EX2, representative of all PGC-1α isoforms) at 8 hours post-treatment, which decreased and returned to baseline at 24 hours (Fig. 1A). PGC-1α1 gene expression was suppressed at 8 hours post-treatment with formoterol and returned to control levels by 24 hours (Fig. 1B). Formoterol induced PGC-1α4 gene expression at 8 hours after treatment (6-fold increase over vehicle) and returned to control levels by 24 hours (Fig. 1C). In contrast, atomoxetine had no effect on EX2 or PGC-1α1 and expression of PGC-1α4 was decreased 20–25% at 16 and 24 hours after treatment (Fig. 1, D–F).

Formoterol, but Not Atomoxetine, Treatment Acutely Increases IGF-1 Gene Expression and Suppresses Myostatin. PGC-1α4 regulates a discrete gene program responsible for inducing skeletal muscle hypertrophy via induction of IGF-1 and suppression of myostatin (Ruas et al., 2012). Formoterol increased IGF-1 gene expression 2-fold at 8 hours post-treatment, which returned to baseline at 24 hours (Fig. 2A). In addition, formoterol suppressed myostatin (MYSTN) gene expression 50% at 16 hours post-treatment (Fig. 2B). Atomoxetine did not alter IGF-1 or MYSTN (Fig. 2, C and D).

Atomoxetine Acutely Increases Phosphorylated mTOR Protein Expression. Formoterol induces skeletal muscle hypertrophy through the Akt-mTOR-rp-S6 pathway (Joassard et al., 2013a,b). In addition, formoterol prevents muscle atrophy via phosphorylation (p) of FoxO3a (Joassard et al., 2013a). Formoterol increased protein expression of p-FoxO3a, p-Akt, p-mTOR and p-rp-S6 8 hours after treatment (Fig. 3, C and D).

Results

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Atomoxetine increased p-mTOR protein expression 24 hours after treatment without altering rp-S6 phosphorylation (Fig. 3, F–J). These results reveal acute formoterol treatment activates hypertrophy pathways via PGC-1α-mediated increases in IGF-1 expression and represses MYSTN expression downstream of p-FoxO3a, p-Akt, p-mTOR and p-S6 (Fig. 4). In contrast, atomoxetine had minimal or no effects on these pathways with the exception of a modest increase in p-mTOR at 24 hours.

Chronic Treatment with Formoterol and/or Atomoxetine Restores Mitochondrial Proteins, Increases Hypertrophy Markers, and Preserves Gastrocnemius Muscle Mass in Mice with Dexamethasone-Induced Muscle Atrophy. Using a previously described model of skeletal muscle atrophy (Wada et al., 2011), chronic treatment with dexamethasone resulted in a 17% reduction in gastrocnemius muscle mass, and low-dose formoterol or atomoxetine prevented this loss (Fig. 5A). After seven daily doses, neither dexamethasone nor atomoxetine treatment had any effect on the expression of PGC-1α mRNA. However, formoterol increased PGC-1α mRNA content (Fig. 5B) but had no effect on mtDNA copy number, as measured by ND1 gene expression (Fig. 5C). Dexamethasone reduced PGC-1α protein 1 week after treatment. In contrast, concomitant treatment of dexamethasone with either formoterol or atomoxetine sustained PGC-1α protein (Fig. 5, D and E). ATP synthase β and mitochondrial cytochrome c oxidase subunit I (COX I) protein expression increased after treatment with formoterol in dexamethasone-treated mice, but there was no effect on NDUFB8 (Fig. 5D). Atomoxetine did not alter mitochondrial protein expression in dexamethasone-treated mice (Fig. 5E). These results reveal that prevention of PGC-1α protein loss by formoterol leads to partial MB with an increase in mitochondrial proteins, whereas atomoxetine prevents PGC-1α protein loss but does not induce MB.

Fig. 5. Chronic effects of atomoxetine and formoterol on skeletal muscle mass and mitochondrial proteins in dexamethasone-treated mice. Mice were coadministered a daily dose of 25 mg/kg water soluble-dexamethasone 0.3 mg/kg of formoterol/0.1 mg/kg of atomoxetine or sterile saline (i.p.) for 7 days. Appropriate saline controls were maintained throughout the experiment. Animals were euthanized after 8 days and gastrocnemius muscle was isolated from both right and the left hind limbs. (A) Normalized gastrocnemius muscle mass 8 days after treating dexamethasone-dosed mice with saline, formoterol, or atomoxetine. Gene expression analysis for PGC-1α (B) and ND1 (C). Representative immunoblots and respective densitometry for mitochondrial proteins: total PGC1α, ATP synthase β, COX-1, and NDUFB8 8 days after either formoterol [BD 0.3 mg/kg; (D)] or atomoxetine [0.1 mg/kg; (E)]. Data were normalized by glyceraldehyde 3-phosphate dehydrogenase (GAPDH). Data are expressed as means ± S.E. (n = 4–5). *Significantly different from either saline-treated controls or all other groups of mice (P ≤ 0.05). **Significantly different from dexamethasone-treated mice (P ≤ 0.05).
IGF-1 gene expression increased with formoterol in dexamethasone-treated mice despite a decrease in the PGC-1α isoform (Fig. 6, A and B). Atomoxetine had no effect on PGC-1α, IGF-1, or MYSTN in dexamethasone-treated mice (Fig. 6, A–C). Formoterol and atomoxetine consistently increased phosphorylation of Akt in dexamethasone-treated mice (Fig. 7). However, only formoterol increased Akt and mTOR phosphorylation and, surprisingly, decreased p-rp-S6 (Fig. 7B). Atomoxetine markedly increased phosphorylation of FOXO3a but did not affect phosphorylation of mTOR or rp-S6 (Fig. 7). Formoterol and atomoxetine prevented the increase in protein expression of MuRF-1 in dexamethasone-treated mice (Fig. 8).

Discussion

Recently, alternative splice variants of PGC-1α have been identified (Ruas et al., 2012), each regulating a discrete gene program. Specifically, induction of the PGC-1α1 isoform regulates MB, whereas PGC-1α4 induces muscle hypertrophy independent of MB (Ruas et al., 2012). A low dose of formoterol (0.3 mg/kg), a long acting β2-adrenergic receptor agonist, stimulated alternative splicing of the PGC-1α gene, increasing PGC-1α4 expression and suppressing PGC-1α1. The induction of PGC-1α4 was associated with the suppression of myostatin and the activation of the Akt-mTOR-rp-S6 pathway in acute naive animals. In unpublished studies, we observed that ICI 118,551, a highly selective β2-adrenergic receptor antagonist, blocked formoterol-induced increases in PGC-1α4 at 16 hours (data not shown). Thus, low-dose formoterol promotes skeletal muscle hypertrophy and prevents protein turnover via the β2-adrenergic receptor.

The observed alterations in the phosphorylation status of FoxO3a, PGC-1α1 protein expression, and the activation of the Akt-mTOR-rp-S6 axis were similar to previously reported data (Pearen et al., 2009; Koopman et al., 2010; Qin et al., 2010). Prior to the discovery of the PGC-1α4 isoform, Pearen et al. (2008, 2009) reported an increase in total PGC-1α gene expression approximately 8 hours post-treatment with formoterol and observed no change in myostatin in the tibialis anterior of naive C57BL/6 mice. In contrast, we found that upregulation of total PGC-1α (EX2) gene expression observed at 8 hours was driven primarily by PGC-1α4 and not the PGC-1α1 isoform. PGC-1α4 is an inducer of IGF-1 (Ruas et al., 2012), which then functions to repress myostatin gene expression. All PGC-1α splice variants contain the exon 2 region and this may explain the disparity between our data and that of (Pearen et al., 2009). Specifically, primers spanning EX2 were incorporated in their studies. Also, the divergence in findings may be attributable to model dissimilarities, including types of skeletal muscle tissue analyzed.

Recently, we reported that atomoxetine, an FDA-approved norepinephrine reuptake inhibitor (NRI) to treat ADHD, stimulates MB in a high throughput screening assay with renal proximal tubules cells (Peterson et al., 2013). Subsequent cheminformatic profiling of the β2-adrenergic receptor agonists and nisoxetine and atomoxetine led to the identification of four chemical moieties shared by atomoxetine and formoterol (Peterson et al., 2013), suggesting that atomoxetine and nisoxetine may
act directly on the β2-adrenergic receptor. Other studies have shown that atomoxetine may activate β-adrenergic receptors indirectly by increasing norepinephrine (Springer et al., 1994; Mirbolooki et al., 2013). Despite chemical similarity to formoterol, acute atomoxetine treatment in naive mice did not increase phosphorylated FoxO3a, activate the Akt-mTOR-rp-S6 axis, or induce skeletal muscle hypertrophy. Additionally, short-term exposure to atomoxetine did not appear to

**Fig. 7.** Chronic effects of atomoxetine and formoterol on protein-synthesis signaling mechanisms in skeletal muscle of dexamethasone-treated mice. Mice were treated as described in Fig. 5. Representative immunoblots and densitometric analysis for markers of muscle protein homeostasis: total and phosphorylated forms of FoxO3a, Akt, mTOR, and ribosomal protein rp-S6 after respective treatments with either formoterol (0.3 mg/kg; (A and B)) or atomoxetine [0.1 mg/kg; (C and D)]. Data were normalized to vehicle and represented as a relative fold-change. Data are expressed as means ± S.E. (n = 4–5). *Significantly different from either saline-treated controls or all other groups of mice (P ≤ 0.05).

**Fig. 8.** Chronic effects of atomoxetine and formoterol on muscle atrophy markers in skeletal muscle of dexamethasone-treated mice. Mice were treated as described in Fig. 5. Representative immunoblots and densitometric analysis for markers of skeletal muscle protein breakdown: MuRF-1 after respective treatments with either formoterol [Form; 0.3 mg/kg; (A)] or atomoxetine [0.1 mg/kg; (B)]. Data are expressed as means ± S.E. (n = 4–5). *Significantly different from saline-treated controls (P ≤ 0.05). #Significantly different from dexamethasone-treated mice (P ≤ 0.05).
modulate PGC-1α1/4 gene expression but did increase p-mTOR, as did formoterol. The interpretation of this finding is difficult given that there are numerous upstream modulators and downstream effectors of mTOR activation. On the basis of these data, we surmise that atomoxetine is not associated with the direct activation of the β-adrenergic receptor and that downstream

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**Fig. 9.** Proposed mechanisms preventing muscle atrophy associated with chronic treatment of atomoxetine or formoterol in skeletal muscle of dexamethasone-treated mice. Chronic formoterol (Form) (A) treatment sustained PGC-1α1 gene and protein expression, leading to increased oxidative phosphorylation proteins. IGF-1 gene expression also increased at this time, but what drives its expression is uncertain (?). Formoterol sustained an increase in phosphorylation of the Akt-mTOR axis, indicating activation and a possible mechanism for protein synthesis. Atomoxetine (Atomox) (B) sustained p-Akt but could not activate the entire axis. In both treatment groups, concomitant inactivation of FoxO3a occurred, as depicted by increased phosphorylation with suppression of MuRF-1 gene expression, blocking a major mechanism for protein degradation. In addition, increased PGC-1α1 observed with either treatment may block the transcription of MuRF-1 and represent an antiatrophic mechanism. Red lines shown are proposed mechanisms for protein degradation with dexamethasone treatment operating through the glucocorticoid receptor (GR). Refer to Fig. 4 for further description of the diagram.
signaling is elicited through an alternative pathway, perhaps related to its NRI pharmacology.

In an atrophy model, treatment with dexamethasone resulted in the activation of atrophic pathways, such as decreases in p-FoxO3a and increased MuRF-1 expression. Dexamethasone treatment also inhibited mTOR, thereby disrupting hypertrophic effects of the IGF-1–Akt-mTOR-rp-S6 axis downstream of IGF-1 (Wang et al., 2006). We observed no change in mTOR or rp-S6 in dexamethasone-treated animals, but we observed evidence of atrophic activation through FoxO3a and increased expression of MuRF-1. We hypothesize that skeletal muscle atrophy in our dexamethasone model was attributable to atrophic mechanisms and not the inactivation of the IGF-1–Akt-mTOR-rp-S6 axis.

As expected, treatment with dexamethasone suppressed PGC-1α1 expression at 8 days; however, concomitant treatment with both formoterol or atomoxetine maintained PGC-1α1 levels equal to that of controls. Interestingly, PGC-1α4 expression declined with formoterol treatment, confirming that formoterol may cause differential expression of these alternatively spliced variants. Despite sustained expression of PGC-1α1, MB was initiated but remained incomplete, as only some mitochondrial proteins increased with formoterol treatment.

It is important to note that p-Akt prevents the dephosphorylation of FoxO3a, limiting its entry into the nucleus and the subsequent induction of MuRF-1 (Sandri et al., 2006). Furthermore, transcriptional activity of nuclear FoxO3a can be inhibited by PGC-1α1 (Sandri et al., 2006). Our observations of increased p-FoxO3a and decreased MuRF-1 with atomoxetine or formoterol treatment provide evidence that atomoxetine and formoterol have antiatrophic properties. Our findings in the dexamethasone study are summarized for formoterol (Fig. 9A) and atomoxetine (Fig. 9B) in a diagram.

Because atomoxetine is an NRI (Bymaster et al., 2002) and norepinephrine has been demonstrated to modulate PGC-1α1 through the β2-adrenergic receptor (Wu et al., 1999), it is plausible that indirect β2-adrenergic receptor agonism by atomoxetine through norepinephrine may explain our results. However, norepinephrine is a less potent stimulator of the β2-adrenergic receptor than formoterol, and downstream signaling events may be more susceptible to internal regulation, a concept that would explain the lack of observable changes in naive mice.

In summary, we have identified formoterol as a potent inducer of skeletal muscle hypertrophy, which is associated with concomitant increases in PGC-1α4 and IGF-1, downregulation of myostatin, and activation of the Akt-mTOR-rp-S6 axis. Formoterol also prevented catabolism, as evidenced by decreases in MuRF-1. In addition, we report that atomoxetine, used at a dose lower than that clinically approved for ADHD, was efficacious in the prevention of skeletal muscle atrophy in a model of dexamethasone-induced muscle atrophy. Furthermore, atomoxetine prevented muscle atrophy by sustaining PGC-1α1 expression, activating Akt, increasing p-FoxO3a, and suppressing MuRF-1. Additional experiments are warranted to define the full dose response of atomoxetine.

Although β2-adrenergic receptor agonists are potent catalytic agents, their potential clinical success for skeletal muscle atrophy is limited by their potential cardiac side effects (Carbo et al., 1997; Soppa et al., 2005; Ryall et al., 2006; Pearen et al., 2009). Atomoxetine did not stimulate skeletal muscle hypertrophy in either of the models tested but was efficacious in preventing atrophy in the dexamethasone model. These characteristics suggest that atomoxetine has potential for therapeutic use in preventing skeletal muscle atrophy.

Authorship Contributions
Participated in research design: Jesinkey, Korrapati, Rasbach, Beeson, Schnellmann.
Conducted experiments: Jesinkey, Korrapati.
Performed data analysis: Jesinkey, Korrapati, Schnellmann.
Wrote or contributed to the writing of the manuscript: Jesinkey, Korrapati, Schnellmann.

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