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Accessibility
Combined administration of testosterone plus an ornithine decarboxylase inhibitor as a selective prostate-sparing anabolic therapy

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Summary

Because of its anabolic effects on muscle, testosterone is being explored as a function-promoting anabolic therapy for functional limitations associated with aging; however, concerns about testosterone’s adverse effects on prostate have inspired efforts to develop strategies that selectively increase muscle mass while sparing the prostate. Testosterone’s promyogenic effects are mediated through upregulation of follistatin. We show here that the administration of recombinant follistatin (rFst) increased muscle mass in mice, but had no effect on prostate mass. Consistent with the results of rFst administration, follistatin transgenic mice with constitutively elevated follistatin levels displayed greater muscle mass than controls, but had similar prostate weights. To elucidate signaling pathways regulated differentially by testosterone and rFst in prostate and muscle, we performed microarray analysis of mRNAs from prostate and levator ani of castrated male mice treated with vehicle, testosterone, or rFst. Testosterone and rFst shared the regulation of transcripts in several growth-promoting pathways, we identified one-responsive gene that is unresponsive to rFst. Accordingly, we administered testosterone with and without α-difluoromethylornithine (DFMO), an Odc1 inhibitor, to castrated mice. DFMO selectively blocked testosterone’s effects on prostate, but did not affect testosterone’s anabolic effects on muscle. Co-administration of testosterone and Odc1 inhibitor presents a novel therapeutic strategy for prostate-sparing anabolic therapy.

Key words: aging; anti-aging; sarcopenia; sex hormones; skeletal muscle; steroids.

Introduction

Testosterone’s anabolic effects on the skeletal muscle are widely recognized (Bhasin et al., 2006). Testosterone levels in men are positively associated with skeletal muscle mass, strength, and physical function (Roy et al., 2002; Orwoll et al., 2006). Consistent with these epidemiological correlations, testosterone administration also increases lean body mass and maximal voluntary strength in men (Bhasin et al., 1996; Bhasin et al., 1997; Snyder et al., 1999; Wang et al., 2000; Page et al., 2005; Srinivas-Shankar et al., 2010). A number of androgens, including testosterone, are being investigated as function-promoting anabolic therapies for the treatment of functional limitations associated with aging and chronic illness (Bhasin et al., 2006). However, concerns about the potential prostatic side effects of testosterone have limited enthusiasm for testosterone’s applications as a function-promoting anabolic therapy in older men (Bhasin et al., 2006; Calof et al., 2005). Thus, there is an unmet need for novel therapeutics that selectively exert anabolic effects on the muscle, but which are free of adverse effects on prostate (Bhasin et al., 2006; Dalton et al., 2011; Basaria et al., 2013). Here, we report a novel strategy for achieving the selectivity of testosterone’s anabolic actions on skeletal muscle while sparing the prostate.

We have reported that testosterone promotes myogenic differentiation of muscle progenitor cells by activating AR/β-catenin pathway and inducing the expression of a number of Wnt-target genes, including follistatin (Singh et al., 2009; Braga et al., 2012). Follistatin is essential for mediating testosterone’s effects on myogenesis; blocking follistatin’s action using either antifollistatin antibodies or siRNAs blocks testosterone’s effects on myogenic differentiation of muscle progenitor cells (Singh et al., 2009; Braga et al., 2012). These data suggested that testosterone and follistatin likely activate analogous pathways in the muscle. We show here that the administration of recombinant follistatin (rFst) increased muscle mass, as expected (Lee, 2007; Kota et al., 2009; Singh et al., 2009; Dalton et al., 2011; Braga et al., 2012), but surprisingly, unlike testosterone, rFst did not affect prostate mass. These data suggested that in prostate, testosterone activates signaling pathways that contribute to prostate growth, but which are not activated by follistatin.

To identify signaling pathways in the prostate that are activated selectively by testosterone, we performed microarray analysis of mRNAs in prostate and levator ani of castrated mice treated with placebo, testosterone, or rFst. Among biological processes that were differentially activated in prostate by testosterone, we identified
polyamine biosynthesis as a key androgen-sensitive pathway that is known to regulate prostate growth (Pegg & Williams-Ashman, 1968; Danzin et al., 1982). Ornithine decarboxylase (Odc1), the rate-limiting enzyme in polyamine biosynthesis, was differentially expressed in the prostate glands of testosterone-treated mice, while showing no significant change in rFst-treated mice. We reasoned that if Odc1 is essential for mediating testosterone’s effects on the prostate, but not the muscle, then the administration of testosterone plus Odc1 inhibitor should block testosterone’s effects on prostate mass, but not on muscle mass. Indeed, we show here that combined administration of testosterone plus α-difluoromethylornithine (DFMO), an irreversible Odc1 inhibitor, increased muscle mass, but did not induce prostatic growth. Thus, combination of testosterone plus an Odc1 inhibitor provides a novel therapeutic approach for achieving the selectivity of testosterone’s effects on the muscle while sparing the prostate.

Results

rFst increases lean mass and decreases fat mass without affecting prostate growth

Previous studies have shown that the effects of testosterone on differentiation of mesenchymal progenitor cells are mediated through follistatin (Singh et al., 2009; Braga et al., 2012). These observations suggested that follistatin might exert effects on androgen-responsive tissues, such as the muscle, fat, and prostate, similar to those of testosterone. Indeed, follistatin has been shown to increase skeletal muscle mass (Lee, 2007; Kota et al., 2009); however, the data on its effects on the prostate and adipose tissue have been discordant (McPherson et al., 1997; Hirai et al., 2007; Flanagan et al., 2009; Tumminello et al., 2010; Nakatani et al., 2011). Higher circulating follistatin levels have been correlated with increased fat mass (Flanagan et al., 2009); follistatin has also been reported to induce adipogenic differentiation of preadipocytes (Hirai et al., 2007). However, transgenic expression of a follistatin peptide in mice was associated with reduced fat accumulation (Tumminello et al., 2010). Follistatin neutralizes activation-mediated suppression of prostate cell growth (McPherson et al., 1997); furthermore, follistatin levels in men with prostate cancer have been associated with increased risk of bone metastasis (Nakatani et al., 2011).

To determine the effects of follistatin on androgen-responsive tissues – muscle, fat, and the prostate, we expressed rFst protein and administered graded doses of rFst to C57BL6 adult male mice (Fig. 1). rFst administration was associated with dose-dependent increases in circulating follistatin levels and lean body mass, measured using nuclear magnetic resonance (Fig. 1A). The wet weights of levator ani, gastrocnemius, and quadriceps femoris muscle groups were related to rFst dose (Fig. 1B) and were significantly higher in mice treated with 100 μg rFst daily than in vehicle-treated mice. rFst administration was associated with a dose-dependent reduction in whole-body and intra-abdominal fat mass (Fig. 1A,C).

Surprisingly, rFst administration did not significantly affect prostate weight (Fig. 1D). Even in mice receiving the highest dose of rFst (100 μg daily), the mean prostate weight was not significantly different from that in vehicle-treated mice, while the levator ani weight was 25% higher than in vehicle-treated controls.

To further characterize the effect of rFst on the growth of prostate cells, we incubated androgen-responsive primary prostate epithelial cells with 0, 5, or 25 ng mL⁻¹ rFst or with methyltrienolone (R1881), a synthetic nonaromatizable androgen (Fig. 1E). As expected, R1881 upregulated the mRNA levels of cell growth marker PCNA, but rFst had no effect on PCNA expression even at concentrations that were nearly 100-fold higher than those in human circulation (O’Connor et al., 1998).

Additionally, we examined the effects of rFST and an androgen, R1881, on the proportion of androgen-sensitive LNCaP cells in S phase in cell cycle analysis using BrdU incorporation combined with DNA intercalation dye 7-AAD. The cell cycle phases of actively dividing LNCaP cells (BrdU+) were resolved using fluorescence-activated cell sorting. Unlike R1881, which increased BrdU incorporation as well as the fraction of LNCaP cells in S phase at concentrations as low as 0.1 nm, rFst had no significant effect on either the percent of BrdU+ cells or the fraction of cells in S phase (Fig. 1F).

Differential effects of follistatin hyperexpression on skeletal muscle mass and prostate in follistatin transgenic mice

Follistatin transgenic mice, in which higher circulating levels of follistatin are derived from its constitutive overexpression in skeletal muscle (Lee, 2007), had higher lean mass than their wild-type littermates (Fig. 2A). The wet weights of levator ani, gastrocnemius, and quadriceps were also significantly higher in follistatin transgenic mice than in wild-type controls (Fig. 2B), even after adjusting for body weights. However, prostate weights did not differ significantly between the follistatin transgenic and wild-type mice (Fig. 2C). These data further support the notion that follistatin selectively promotes muscle growth, but spares the prostate.

Microarray analysis of genes and pathways differentially regulated by testosterone and rFst in the muscle and prostate

As follistatin is in the signaling pathway that mediates the effects of testosterone on myogenesis, the observations that rFst selectively increased skeletal muscle mass, but did not affect prostate growth or the markers of prostate cell proliferation in vitro, suggested that testosterone differentially activates specific signaling pathways in the prostate that are not activated by rFst. We surmised that signaling pathways that are activated in prostate by testosterone, but not by rFst, are the likely mediators of testosterone’s effects on the prostate and would be of interest with respect to developing therapeutic strategies for achieving the selectivity of testosterone’s actions.

Accordingly, we used microarray analysis to characterize the transcriptome of levator ani and prostate under the following conditions: (i) intact male mice, (ii) castrated male mice treated with vehicle alone, (iii) castrated male mice treated with testosterone, and (iv) castrated male mice treated with rFst. A minimum of four replicates were run for each group. A gene was considered androgen sensitive if it was differentially expressed at a q-value < 0.2 comparing intact to castrated mice and castrated mice to testosterone-treated castrated mice. Similarly, a gene was considered follistatin sensitive if it was differentially expressed at a q-value < 0.2 comparing intact to castrated mice and castrated mice to follistatin-treated castrated mice.

After compiling the lists of genes classified as androgen sensitive and follistatin sensitive, Gene Ontology (GO) term enrichment analysis was performed to identify GO terms over-represented in either category (Table S1). There were 852 genes classified as androgen sensitive and 778 classified as follistatin sensitive in the levator ani (Fig. 3A,B). Of these genes, 391 were found to be both androgen and follistatin sensitive. As expected from the anabolic effects of both testosterone and follistatin on skeletal muscle, GO term enrichment revealed a large number of biological processes related to cell growth and development (Fig. 3B).
Microarray analysis of prostate yielded results that were strikingly different from those in the muscle (Fig. 3A–C). We identified 593 androgen-sensitive genes, but only 9 follistatin-sensitive genes. Of the nine follistatin-sensitive genes, seven were also androgen sensitive.

These microarray analyses are consistent with the observations that testosterone promotes the growth of both muscle and prostate, while rFst only affects muscle growth, but spares the prostate.

The microarray data provide a basis from which we can identify biological processes that can be targeted to reduce the androgenic effects of testosterone on the prostate. Among the biological pathways that were activated in the prostate selectively by testosterone (Fig. 3B; Fig. S1), we identified polyamine biosynthetic pathway as a key target for several reasons. First, polyamine synthesis was androgen sensitive, but not follistatin sensitive, in the prostate; this pathway was not among those differentially induced by testosterone and rFst in levator ani.

Second, polyamine biosynthesis is known to be important in the regulation of prostate growth (Pegg & Williams-Ashman, 1968; Danzin et al., 1982). Third, ornithine decarboxylase (Odc1), a key enzyme in polyamine biosynthesis, exhibited an expression signature indicative of its differential regulation by testosterone in the prostate (Fig. 3C,
Fig. 2  Differential effects of follistatin hyperexpression on skeletal muscle mass and prostate in follistatin transgenic mice. (A) Follistatin transgenic mice (Fst Tg) had significantly higher lean body mass than wild-type controls. (B) Follistatin transgenic mice had higher weights of levator ani, gastrocnemius, and quadriceps femoris than wild-type controls. (C) Prostate weights did not differ significantly between follistatin transgenic mice and wild-type controls. **P < 0.05 vs. wild-type controls.

Fig. 3  Microarray analysis of testosterone and rFst in the muscle and prostate. (A) The heatplots represent the statistically significant genes (q-value < 0.2) in the levator ani and prostate for the listed experimental condition comparisons across untreated (Sham), castrated (Cx), testosterone-treated (Tes), and follistatin-treated (Fst) mice. Heatplots were classified into the following groups: uniquely androgen sensitive, uniquely follistatin sensitive, and both androgen and follistatin sensitive. (B) The venn diagram represents the number of genes that are differentially expressed in the categories taken from the heatplots. Gene Ontology (GO) term enrichment analysis was performed on the associated sets of genes. Selected GO terms that are significant at an adjusted P-value < \(10^{-3}\) are listed. Follistatin treatment has a negligible effect on the prostate and no enriched GO terms. (C) Gene expression ratios (log2 fold change) and the statistical significance of the ratios (q-value) are shown for ornithine decarboxylase (Odc1). Odc1 is androgen sensitive, but not follistatin sensitive, in the prostate, and no effect is seen in the levator ani.

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Inhibition of Odc1 by DFMO blocks testosterone’s effects on the prostate while retaining its anabolic effects on the muscle

We reasoned that if Odc1 were essential for mediating testosterone’s effects on the prostate, but not the muscle, then the inhibition of Odc1 activity would be expected to attenuate the prostate-stimulating effects of testosterone while retaining its anabolic effects on the muscle. Accordingly, adult male intact and castrated mice were treated for 2 weeks with vehicle or testosterone with and without DFMO, a specific Odc1 inhibitor, as follows: intact (), castrated (Cx), castrated +15 µg per day testosterone (Cx+T), and castrated +15 µg per day testosterone +15 µg per day DFMO (Cx+T+DFMO). The doses and duration of DFMO treatment were based on previous studies that demonstrated effective inhibition of ODC activity in vivo (Danzin et al., 1982).

As expected, castrated mice had significantly lower levator ani weight as well as lower prostate weight than intact controls (Fig. 4A,B). Testosterone administration alone in castrated mice restored the weights of prostate and levator ani muscle to those observed in intact eugonadal controls. Importantly, combined administration of testosterone plus DFMO restored levator ani mass to that of intact controls and testosterone-treated castrated mice. However, prostate weights in castrated mice treated with testosterone plus DFMO were significantly lower than those of intact controls. Furthermore, testosterone administration prevented the involution of prostate gland and lumen observed in castrated mice; co-administration of DFMO blocked the testosterone’s effect on prostate epithelial growth (Fig. 4C). Thus, Odc1 is essential for mediating testosterone’s effects on the prostate, but not muscle.

Discussion

The past decade has witnessed enormous pharmaceutical interest in the development of selective androgen receptor modulators (SARMs) that have preferential anabolic effects on the muscle, but which are relatively selective with respect to the prostate (Bhasin et al., 2006; Dalton et al., 2011; Basaria et al., 2013). We report here two novel therapeutic strategies for achieving the selectivity of anabolic effects on the skeletal muscle while sparing the prostate. We show that Odc1, a rate-limiting enzyme in the polyamine biosynthetic pathway, is an important mediator of testosterone’s effects on the prostate and that the administration of
testosterone in combination with an Odc1 inhibitor blocks testosterone's effects on the prostate, but not on the muscle. Additionally, we show here that follistatin, a mediator of testosterone's effects on myogenesis, selectively increases skeletal muscle mass without affecting the prostate. Although both strategies could potentially exert anabolic effects while sparing the prostate, the testosterone plus Odc1 inhibitor combination could be attractive to patient populations in whom improvements in sexual function may be a desired outcome. Furthermore, testosterone and DFMO have been administered previously to humans and approved by FDA for other indications; therefore, they provide an accelerated path to clinical application.

Ornithine decarboxylase is a widely distributed enzyme that is expressed in the prostate as well as in the skeletal muscle (Pegg & Williams-Ashman, 1968; Pegg, 1988; Jänne et al., 1991; Lee et al., 2011). Polyamine synthesis has been implicated in the regulation of prostate growth (Pegg, 1988; Jänne et al., 1991). The enzyme, ornithine decarboxylase, the first enzyme in the polyamine synthesis that converts ornithine to putrescine, has been shown to interact directly with androgen receptor, contains an AR-binding site in its promoter, and plays an important role in the regulation of prostate growth (Pegg & Williams-Ashman, 1968; Danzin et al., 1982). The polyamines are essential for proliferating cells (Pegg, 1988), especially in the prostate. Testosterone has been reported to regulate ornithine decarboxylase in the muscle and prostate (Jänne et al., 1991). Our data demonstrate that Odc1 is essential for mediating testosterone's effects on the prostate, but not on the muscle. These observations suggest that the combination of testosterone plus DFMO or other Odc1 inhibitors can serve as selective androgen therapy that spares the prostate. Odc1 is an attractive therapeutic target due to its short half-life and because a number of Odc1 inhibitors have been developed previously for other indications (Abeloff et al., 1984; Boitz et al., 2009). Separately, testosterone and DFMO each have been administered previously to humans for other indications. Testosterone alone has been used for the treatment of hypogonadism in men, while DFMO alone has been used for the treatment of leshmaniasis, hirsutism, and other disorders (Abeloff et al., 1984; Bhasin et al., 2006; Boitz et al., 2009). Preclinical and clinical data on their safety when they are administered alone are available. Thus, the combination of testosterone plus DFMO combination could proceed to clinical trials with more limited preclinical Toxicology studies than are typically required for completely new molecules.

While we have focused on the Odc1 pathway because of its known role in prostate growth, it is possible that additional pathways may play an important direct or indirect role in mediating testosterone's effects on the prostate. In addition to the prostate and muscle, testosterone regulates other physiological processes, including erythropoiesis, bone health, secondary sex characteristics, and sexual function. While we have shown that the Odc1 inhibitor, DFMO, blocks the prostate effects of testosterone without attenuating its anabolic effects on the muscle, additional studies are needed to ensure that other physiological effects of testosterone, especially on sexual function and bone, are not attenuated by the administration of an Odc1 inhibitor.

This drug combination would be particularly attractive for the treatment of conditions in which testosterone therapy alone may be associated with a high risk of adverse prostate events, such as older men with low testosterone levels, hypogonadal men at increased risk of prostate cancer, or men with prostate cancer who have undergone radical prostatectomy and are at low risk of disease recurrence. Accordingly, the therapeutic applications of the combination of testosterone plus DFMO or other Odc1 inhibitors as selective androgen/ anabolic therapy that spares the prostate should be explored.

**Methods**

**Expression and purification of human Fst288 (rFst)**

Follistatin 288 (Fst288, amino acid residues 30–317) cDNA was cloned into SalI/Xho1 site of pET30 and expressed with His-tag in E. coli BL21 (DE3) after induction with IPTG. Cell lysate was centrifuged and the pellet was solubilized in a buffer containing 50 mM Tris–HCl, 8 M urea, 100 mM PMSF, pH 8.0. His-tagged Fst288 was purified with HisPur cobalt spin column (Thermo scientific, Rockford, IL, USA). Purified protein in elution buffer containing 8 M urea was diluted 1:4 with 200 mM Tris–HCl, pH 10, and 2 mM DTT and dialyzed against Tris buffer (10 mM Tris–HCl, 1 mM NaCl, pH 8.0) at 4°C. Purified protein was passed through Endotoxin Removal Gel and stored at ~80°C in 20% glycerol.

**rFst administration**

Eight-week-old C57BL6 mice (Jackson Laboratory, Bar Harbor, ME, USA) were housed in Laboratory Animal Science Center, using the protocols approved by the Institutional Animal Care and Use Committee of Boston University.

Animals were allowed to recover for 1 week before random assignment to one of four groups (n = 6 in each group) to receive 0, 10, 30, or 100 μg rFst in phosphate-buffered saline containing 20% glycerol by daily subcutaneous injection for 13 weeks. Body weights and lean and fat mass were measured weekly using EchoMRI-700 (Echo Medical System, Houston, TX, USA). Wet weights of muscle groups and dorsal prostate were measured after euthanasia.

**Microarray transcriptome analysis**

Ten-week-old male mice were randomized to one of four groups: sham (control) operated, vehicle treated (n = 4), castrated, vehicle treated (n = 4), castrated+ testosterone treated (15 μg daily; n = 4), and castrated + rFst treated (15 μg daily; n = 4). Mice underwent castration under ketamine–xylazine, allowed to recover for 2 weeks, and injected subcutaneously with vehicle, 15 μg testosterone, or 15 μg rFst. The mice were euthanized after 24 h, and prostate and levator ani muscle were harvested.

Total RNA was prepared, and biotin-labeled cDNA was hybridized to Affymetrix Mouse 430 2.0 chips. Raw data were background-corrected, quantile-normalized, and summarized into log-transformed expression values using median polish according to RMA methodology (Irizarry et al., 2003).

Differential expression calculations were made using linear models to calculate a moderated t-statistic as detailed in Smyth (2004). A Benjamini–Hochberg correction was used to account for multiple hypothesis testing. All statistical calculations were made using limma package in R statistical program (http://bioconductor.org/packages/ release/bioc/html/limma.html; http://www.rproject.org/ftp/ftp. informatics.jax.org/pub/reports/index.html#go). A gene was classified...
as ‘androgen sensitive’ if it showed differential expression at a q-value < 0.2 under these two comparisons: (i) castrated versus sham-treated mice and (ii) testosterone-treated versus castrated mice. A gene was classified as ‘follistatin sensitive’ if it showed differential expression at a q-value < 0.2 under these two comparisons: (i) castrated versus sham-treated mice and (ii) rFst-treated versus castrated mice.

Gene Ontology term enrichment was used to identify biological processes over-represented in sets of genes identified through gene expression analysis. Gene annotations were limited to ‘biological process’ branch of the ontology and downloaded from the Mouse Genome Informatics (MGI) database. GO is a hierarchy, gaining biological specificity the further a term is away from the root. This parent–child relationship implies that a gene annotated to a child term is also annotated to the parent term, which in turn is annotated to all descendant terms. Accordingly, gene annotations were mapped to the GO and a gene was subsumed by all parent terms. This results in the root term, biological process, being annotated to all genes. The revised gene to GO term mapping was then filtered to GO terms with very high frequency and very low frequency. We required a term to have <300 and >5 associated genes for further analysis. For a set of genes, GO term enrichment for term i was calculated using hypergeometric function,

\[ F_i(x, k; m, n) = \frac{\binom{m}{k} \binom{n}{x-k}}{\binom{m+n}{k}}, \]

where m is the number of genes that term i is annotated to cover the entire dataset, n is the number of genes that are annotated with any GO term over the entire dataset, k is the number of genes that are selected, and x is the number of times term i is selected from k genes.

**Time-course experiments of testosterone administration in castrate mice**

Eight-week-old C57BL6 mice (Jackson Laboratory) were housed in Laboratory Animal Science Center, using the protocols approved by the Institutional Animal Care and Use Committee of Brigham and Women’s Hospital. Animals were allowed to recover for 1 week before random assignment to one of three groups (n = 6 in each group): intact, castrated, or castrated + T to receive oil, oil, and oil + 30 μg T subcutaneously, respectively. The animals were euthanized at days 1, 3, 7, and 14 after the start of treatment. Wet weights of dorsal prostate tissues were weighed. prostate-sparing anabolic therapy, R. Jasuja et al. (2013) published by the Anatomical Society and John Wiley & Sons Ltd.

**References**


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## Supporting Information

Additional Supporting Information may be found in the online version of this article at the publisher’s web-site.

**Fig. S1** Comparison of pathway expression for the prostate on a subnetwork centered on the Gene Ontology (GO) term, ‘polyamine biosynthetic process.’

**Fig. S2** Differential regulation of Odc1 mRNA expression in prostate tissues obtained from castrated mice after testosterone and Fst treatments.

**Fig. S3** Recombinant Fst does not affect Odc1 protein expression in LncAP cells.

**Fig. S4** Odc1 expression is consistently upregulated by testosterone supplementation in castrated mice in vivo.

**Fig. S5** Effect of castration and testosterone supplementation on prostate weights in mice.

**Table S1** Gene expression analysis for identifying androgen-sensitive and follistatin-sensitive genes in the prostate and levator ani, along with Gene Ontology (GO) term enrichment analysis for the associated sets of genes.

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