

# Glutamine prevents myostatin hyperexpression and protein hypercatabolism induced in C2C12 myotubes by tumor necrosis factor- $\alpha$

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**Abstract** Depletion of skeletal muscle protein mainly results from enhanced protein breakdown, caused by activation of proteolytic systems such as the  $\text{Ca}^{2+}$ -dependent and the ATP-ubiquitin-dependent ones. In the last few years, enhanced expression and bioactivity of myostatin have been reported in several pathologies characterized by marked skeletal muscle depletion. More recently, high myostatin levels have been associated with glucocorticoid-induced hypercatabolism. The search for therapeutical strategies aimed at preventing/correcting protein hypercatabolism has been directed to inhibit humoral mediators known for their pro-catabolic action, such as TNF $\alpha$ . The present study has been aimed to investigate the involvement of TNF $\alpha$  in the regulation of both myostatin expression and intracellular protein catabolism, and the possibility to interfere with such modulations by means of amino acid supplementation. For this purpose, C2C12 myotubes exposed to TNF $\alpha$  in the presence or in the absence of amino acid (glutamine or leucine) supplementation have been used. Myotube treatment with TNF $\alpha$  leads to both hyperexpression of the muscle-specific ubiquitin ligase atrogen-1, and enhanced activity of the  $\text{Ca}^{2+}$ -dependent proteolytic system. These changes are associated with increased myostatin expression. Glutamine supplementation effectively prevents TNF $\alpha$ -induced muscle protein loss and restores normal myostatin levels. The

results shown in the present study indicate a direct involvement of TNF $\alpha$  in the onset of myotube protein loss and in the perturbation of myostatin-dependent signaling. In addition, the protective effect exerted by glutamine suggests that amino acid supplementation could represent a possible strategy to improve muscle mass.

**Keywords** Myostatin · TNF $\alpha$  · Muscle wasting · Amino acids · Protein breakdown

## Introduction

Skeletal muscle is the most abundant tissue and the major protein reservoir in the human body. Muscle mass usually results from a dynamic balance between protein synthesis and degradation (Goll et al. 1989; Sandri 2008). Indeed, alterations between anabolic and catabolic pathways may lead to either muscle hypertrophy or atrophy, respectively (Guttridge 2004; Ventadour and Attaix 2006). The latter, in particular, is peculiar to conditions such as disuse (e.g., immobilization, muscle unloading, denervation), aging, starvation, and disease states (among which muscle dystrophies, diabetes, and cancer) usually characterized by the occurrence of ‘cachexia’ (reviewed in Jackman and Kandarian 2004; Sandri 2008).

Depletion of skeletal muscle protein may result from reduced rates of protein synthesis, enhanced rates of proteolysis, or both, although increased protein breakdown, mainly caused by activation of proteolytic systems such as the  $\text{Ca}^{2+}$ -dependent and the ATP-ubiquitin-dependent ones is believed to play a crucial role (reviewed in Ventadour and Attaix 2006). In this regard, a subset of genes, known as ‘atrogenes’, have been found upregulated in different models of muscle atrophy. These include two muscle-specific

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ubiquitin ligases, namely atrogin-1 and MuRF-1, which are associated with protein degradation through the ubiquitin–proteasome system (Bodine et al. 2001; Gomes et al. 2001). Recently, a role for the acidic vacuolar proteolysis has emerged (Capel et al. 2009).

The search for strategies aimed at preventing/correcting protein hypercatabolism has significantly increased in the last years. In this regard, previous studies have shown that amino acid supplementation counteracts muscle wasting, although the underlying mechanisms remain unclear. Indeed, glutamine administration has been reported to prevent muscle protein breakdown in septic rats (Hickson et al. 1995). Similarly, leucine supplementation to both animals and humans has been shown to stimulate muscle protein synthesis and to modulate the activity of proteins involved in the control of mRNA translation, thus resulting in suppressed skeletal muscle proteolysis (Nair et al. 1992; Louard et al. 1995; Sugawara et al. 2009). Finally, glucocorticoid-induced muscle wasting is prevented in dexamethasone-treated rats fed a glutamine-enriched diet (Ma et al. 2003; Salehian et al. 2006).

Most of the therapeutical strategies proposed in the literature have been directed to inhibit humoral mediators known for their pro-catabolic action, such as TNF $\alpha$ . Indeed, increased nitrogen and amino acid efflux from skeletal muscle and loss of body protein have been shown in mice administered TNF $\alpha$  (Hoshino et al. 1991; Buck and Chojkier 1996; Lang et al. 2002), in animals expressing a TNF $\alpha$  transgene, as well as in conditions characterized by elevated endogenous TNF $\alpha$ , i.e., experimental sepsis (Ahmad et al. 1994) or cancer (Costelli et al. 1993). Most of these effects can be counteracted by treatment with anti-TNF $\alpha$  antibodies, or by either knocking-down the cytokine receptors or overexpressing soluble receptor isoforms (reviewed in Argiles and Lopez-Soriano 1999).

In the last few years, significant progress has been made in identifying signaling pathways potentially contributing to muscle atrophy, with particular reference to that activated by a TGF $\beta$  family member known as myostatin. This is synthesized as an inactive precursor protein, that, after proteolytic cleavage, can dimerize to give the active peptide (McPherron et al. 1997; Lee and McPherron 2001). Once secreted, myostatin circulates as an inactive latent and highly conserved dimer bound to the propeptide or to other myostatin-binding proteins, such as follistatin (Lee and McPherron 2001).

Following activation myostatin binds with high affinity the activin type IIB receptor (ActRIIB), that in turn recruits a type I receptor (ALK-4 or ALK-5), to form a heteromeric complex (Lee and McPherron 2001; Rebbapragada et al. 2003). Subsequently, recruitment and phosphorylation of signal transducers Smads 2 and 3, and their interaction with co-Smad 4, result in the translocation of this complex to the

nucleus, where it regulates the transcription of myostatin target genes (Zhu et al. 2004).

Myostatin is hyperexpressed in several conditions associated with muscle atrophy (Gonzalez-Cadavid et al. 1998; Zimmers et al. 2002; Holzbaur et al. 2006). In particular, we have recently reported that muscle myostatin signaling is enhanced in two different experimental models of cancer cachexia (Costelli et al. 2008; Bonetto et al. 2009). This upregulation seems to depend, partially at least, on TNF $\alpha$ . Indeed, administration of pentoxifylline, an inhibitor of TNF $\alpha$  synthesis, improves skeletal muscle wasting in tumor bearers and restores the myostatin/follistatin ratio (Costelli et al. 2008).

The present study has been aimed to investigate whether TNF $\alpha$  could be directly involved in the regulation of myostatin expression and whether amino acid supplementation could both prevent TNF $\alpha$ -induced hypercatabolism and myostatin upregulation. For this purpose, C2C12 myotubes exposed to TNF $\alpha$  in the presence or in the absence of an excess of amino acid (glutamine or leucine) have been used as an *in vitro* model system. Both the state of activation of the myostatin signaling pathway and the modulations of protein hypercatabolism have been assessed.

## Materials and methods

### Cell culture

Murine C2C12 skeletal myoblasts (ATCC, Manassas, VA, USA) were grown in high glucose Dulbecco's Modified Eagle's Medium (DMEM) supplemented with 10% FBS, 100 U/ml penicillin, 100 mg/ml streptomycin, 100 mg/ml sodium pyruvate, 2 mM L-glutamine (all reagents were supplied by Sigma–Aldrich, Milan, Italy), and maintained at 37°C in a humidified atmosphere of 5% CO<sub>2</sub> in air. Cultures were regularly checked for mycoplasma contamination by staining with the DNA specific fluorochrome 4'-6-diamidine-2-phenylindole dihydrochloride (DAPI; Boehringer, Mannheim, Germany). For the experiments, cells were seeded at 35,000/cm<sup>2</sup> to obtain full confluence 24 h later. Differentiation to myotubes was induced by shifting confluent cultures to DMEM supplemented with 2% horse serum (DM). The medium was changed every second day, and within 5 days most of the cells were fused to form myotubes. On day 6, the cultures were exposed to 100 ng/ml TNF $\alpha$  (Immunological Sciences, Rome, Italy), and cells collected after 24 h. Both TNF $\alpha$ -treated and untreated cultures were photographed under phase contrast microscopy, and monolayers were stored at –80°C for further analysis.

In a different set of experiments, C2C12 cells were induced to differentiate to myotubes (see above) in DM

enriched in either glutamine (8 mM; Salehian et al. 2006) or leucine (2 mM; Du et al. 2007). The medium was changed every second day, maintaining glutamine or leucine excess. At day 6 of differentiation, myotubes were treated with TNF $\alpha$  (100 ng/ml) for 24 h (if not otherwise specified). These experimental conditions allowed to evaluate whether excess amino acid could affect both TNF $\alpha$ -induced protein hypercatabolism and myostatin bioactivity.

### Morphological analyses

To evaluate nuclear morphology, cells were grown on chamber slides (Nalge Nunc International, Naperville, IL, USA) and treated as described above. Monolayers were then washed with PBS, fixed in 95% ethanol, stained with the DAPI fluorochrome (10 ng/ml, dissolved in methanol), mounted in Mowiol (Calbiochem, La Jolla, CA, USA), and viewed in an epi-illuminated fluorescence microscope (Dialux 20, Leitz, Germany).

Alternatively, in order to assess myosin heavy-chain expression and localization, after complete differentiation myotubes were washed in PBS, fixed in acetone-methanol solution (1:1) for 20 min at  $-20^{\circ}\text{C}$  and then probed with the primary mouse monoclonal antibody (Clone MY32; Sigma-Aldrich, Milan, Italy). Detection was performed using a Cy3-conjugated mouse IgG secondary antibody (GE Healthcare, Milano, Italy). Nuclei were stained with the DAPI fluorochrome and the images captured in an epi-illuminated fluorescence microscope (Axiovert 35, Zeiss, Germany).

### Calpain enzymatic activity

Calpain activity in C2C12 myotubes was determined by evaluating the cleavage of a specific fluorogenic substrate (see Beyette et al. 1998; Ruiz-Vela et al. 1999). Fresh cells were lysed in 50 mM Tris-HCl pH 7.6, 150 mM NaCl, 10 mM NaH<sub>2</sub>PO<sub>4</sub>, 10 mM Na<sub>2</sub>HPO<sub>4</sub>, 1% (v/v) Nonidet P-40, 0.4 mM Na<sub>3</sub>VO<sub>4</sub>, and then centrifuged at 13,000 g for 15 min at  $4^{\circ}\text{C}$ . The supernatant was collected

and protein concentration determined by the method of Lowry et al. (1951).

Aliquots of 50  $\mu\text{g}$  protein were then incubated for 60 min at  $37^{\circ}\text{C}$  in the presence of the a specific fluorogenic substrate (Suc-Leu-Tyr-AMC, Calbiochem, La Jolla, CA, USA). The incubation buffer for the evaluation of calpain activity was 25 mM HEPES pH 7.5, 0.1% CHAPS, 10% sucrose, 10 mM dithiothreitol, 0.1 mg/ml ovalbumin.

Fluorescence was read with a spectrofluorometer (380 nm excitation–460 nm emission; Perkin-Elmer, Norwalk, CT, USA). The activity, expressed as nkatal/mg protein (1 katal = 1 mol substrate hydrolyzed/s) was calculated by using free AMC as working standard.

### Reverse transcription-PCR

Total RNA was obtained using the TriPure reagent (Roche, Indianapolis, IN, USA) following the instructions provided by the manufacturer. RNA concentration was determined spectrophotometrically (SmartSpec 3000, Bio-Rad, Hercules, CA, USA) and its purity ensured by evaluating the 260/280 nm ratio. RNA integrity was checked by electrophoresis on 1.2% agarose gel, containing morpholino propane-sulfonic acid (MOPS) 0.02 M and 18% formaldehyde.

Atrogin-1 mRNA levels were determined by semi-quantitative reverse-transcription polymerase chain reaction using the kit ‘Ready-to-Go RT-PCR Beads’ (GE Healthcare, Milano, Italy). Following manufacturer’s protocol, 0.5  $\mu\text{g}$  total RNA and 400 nM mixture of each couple of primers were added to a RT-PCR reaction mixture containing  $\sim 2.0$  units *Taq* DNA-polymerase, 10 mM Tris-HCl pH 9.0, 60 mM KCl, 1.5 mM MgCl<sub>2</sub>, 200  $\mu\text{M}$  dNTP, Moloney murine leukemia virus (M-MuLV) reverse transcriptase, ribonuclease inhibitor and stabilizers to reach a final volume of 50  $\mu\text{l}$  in each reaction tube. Table 1 shows primers sequences and accession numbers for mouse atrogin-1 and glyceraldehyde-3-phosphate dehydrogenase (GAPDH), that were obtained according to published sequences (Invitrogen, Milano, Italy).

**Table 1** RT-PCR primers and amplification conditions

Gene	Primer sequences	Amplification	Cycles
<i>Atrogin-1</i> (NM_026346)	5'-CCATCAGGAGAAGTGGATCTATGTT-3'	1 min, $94^{\circ}\text{C}$	30
	5'-GCTTCCCCCAAAGTGCAGTA-3'	1 min, $60^{\circ}\text{C}$	
		1 min, $72^{\circ}\text{C}$	
<i>GAPDH</i> (AF_106860)	5'-TGCAACCACTGCTTA-3'	1 min, $94^{\circ}\text{C}$	20
	5'-GGATGCAGGGATGATGTTC -3'	1 min, $60^{\circ}\text{C}$	
		1 min, $72^{\circ}\text{C}$	

Retrotranscription was performed at 42°C for 30 min, and before entering the cycling protocol the samples were denatured (2 min, 95°C). Amplification conditions are reported in Table 1. Both positive and negative controls were performed. PCR products (atrogen-1: 75 bp; GAPDH: 177 bp) were electrophoresed on 2% agarose gels and visualized with ethidium bromide. A 100-bp-standard DNA ladder (Fermentas, Burlington, ON, Canada) was used to estimate the length of each PCR product. Quantification was performed by densitometric analysis. The results were normalized according to GAPDH gene expression. Comparisons among groups were made in the linear phase of amplification.

#### Western blotting

C2C12 myotubes ( $\sim 1.5 \times 10^6$  cells) were homogenized in 80 mM Tris-HCl, pH 6.8 (containing 1 mM DTT, 70 mM SDS, and 1 mM glycerol), kept on ice for 30 min, centrifuged at  $15,000 \times g$  for 10 min at 4°C, and the supernatant collected. Protein concentration was assayed according to Lowry et al. (1951) using BSA as working standard. Equal amounts of protein (30 µg) were heat-denatured in sample-loading buffer (50 mM Tris-HCl, pH 6.8, 100 mM DTT, 2% SDS, 0.1% bromophenol blue, 10% glycerol), resolved on a SDS-PAGE (12% polyacrylamide, 0.1% SDS) and transferred for 2 h to nitrocellulose membranes (Bio-Rad, Hercules, CA, USA). Protein transfer was checked by Ponceau S staining. The filters were then blocked with Tris-buffered saline (TBS) containing 0.05% Tween and 5% non-fat dry milk and incubated overnight with a polyclonal anti-myostatin antibody (1:1,000; Società Italiana Chimici, Roma, Italy), specific for the  $\sim 30$  kDa processed myostatin, raised against a synthetic peptide (aa 133–148) representing a portion of human GDF-8 encoded within exon 3 (LocusLink ID 2660); a goat polyclonal anti-follistatin antibody (1:200, Santa Cruz Biotechnology, Santa Cruz, CA, USA) raised against a peptide mapping within an internal region of follistatin of human origin ( $\sim 36$  kDa); a mouse monoclonal anti-calpain-1 antibody (1:1,000; VWR International, Milan, Italy), recognizing the  $\sim 80$  kDa active form of calpain-1. Antibody against atrogen-1 ( $\sim 41$  kDa) and MyHC ( $\sim 220$  kDa) were from ECMbiosciences (Versailles, KY, USA), and Sigma (St. Louis, MO, USA), respectively.

Goat anti-rabbit, goat anti-mouse (Bio-Rad, Hercules, CA, USA) or rabbit-anti-goat (Millipore, Vimodrone, MI, Italy) peroxidase-conjugated IgG were used as secondary antibodies.

The filters were then stripped by incubation in 62.5 mM Tris-HCl, pH 6.7, containing 100 mM 2-mercaptoethanol and 2% SDS for 30 min at 50°C, and reprobed with a mouse polyclonal antibody directed against tubulin

( $\sim 50$  kDa; Sigma, St. Louis, MO, USA) to normalize sample loading. The membrane-bound immune complexes were detected by enhanced chemiluminescence (Santa Cruz Biotechnology, USA) on a photon-sensitive film (Hyperfilm ECL; GE Healthcare, Milano, Italy). Band quantification was performed by densitometric analysis with a specific software (TotalLab, NonLinear Dynamics, Newcastle upon Tyne, UK).

#### Electrophoretic mobility-shift assay (EMSA)

To prepare nuclear extracts (Blough et al. 1999) C2C12 myotubes ( $\sim 1.5 \times 10^6$  cells) were homogenized in ice cold 10 mM HEPES, pH 7.5, containing 10 mM MgCl<sub>2</sub>, 5 mM KCl, 0.1 mM EDTA pH 8.0, 0.1% Triton X-100, 0.1 mM phenylmethanesulfonyl fluoride (PMSF), 1 mM DTT, 2 µg/ml aprotinin, 2 µg/ml leupeptin. Samples were then centrifuged (5 min, 3,000 g), pellets resuspended in ice cold 20 mM HEPES, pH 7.9, containing 25% glycerol, 500 mM NaCl, 1.5 mM MgCl<sub>2</sub>, 0.2 mM EDTA, pH 8.0, 0.2 mM PMSF, 0.5 mM DTT, 2 µg/ml aprotinin, 2 µg/ml leupeptin, and incubated on ice for 30 min. Cell debris were removed by centrifugation (5 min, 3,000 g) and the supernatant collected and stored at  $-80^\circ\text{C}$ . SMAD and NF- $\kappa$ B oligonucleotides were purchased from Santa Cruz Biotechnology (Santa Cruz, CA, USA) and Promega (Milan, Italy), respectively (Table 2). Oligonucleotide labeling and binding reactions were performed by using the reagent supplied in the Gel Shift Assay System (Promega, Milano, Italy). Binding reaction mixtures, containing nuclear proteins (10 µg) and gel shift binding buffer (10 mM Tris-HCl, pH 7.5, containing 1 mM MgCl<sub>2</sub>, 0.5 mM EDTA, 0.5 mM DTT, 50 mM NaCl, 0.05 µg/µl poly(dI-dC) poly(dI-dC), 4% glycerol), were incubated at room temperature for 10 min in the presence of 0.035 pmol <sup>32</sup>P-ATP end-labeled double-stranded oligonucleotide. At the end of the incubation, samples were electrophoresed in 0.5  $\times$  Tris-borate-EDTA (TBE) buffer at 350 V for 40 min on a 4% nondenaturing acrylamide gel. The gel was dried for 45 min and exposed overnight or longer to a film for autoradiography (GE Healthcare, Milano, Italy) at  $-80^\circ\text{C}$  with intensifying screens. Specificity of the bands was confirmed by adding an excess amount of aspecific oligonucleotide (1.75 pmol) to a control sample. HeLa cell

**Table 2** EMSA oligonucleotides

Transcription factor	Sequence
SMAD	5'-AGTATGTCTAGACTGA-3' 3'-TCATACAGATCTGACT-5'
NF- $\kappa$ B	5'-AGTTGAGGGGACTTTCCCAGGC-3' 3'-TCAACTCCCCTGAAAGGGTCCG-5'



nuclear extract was used as positive control (Promega, Milano, Italy).

#### Data analysis and presentation

All results were expressed as mean  $\pm$  SD. Significance of the differences was evaluated by analysis of variance (ANOVA) followed by Tukey's test.

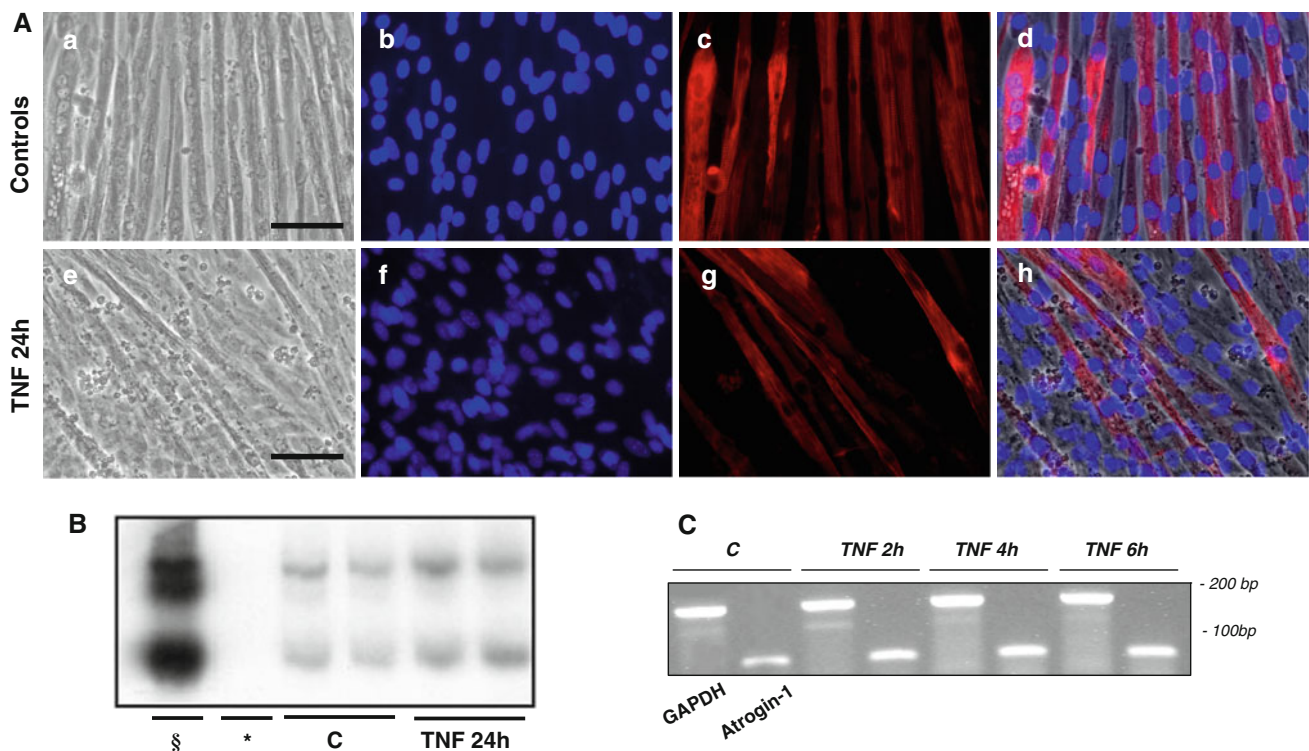
### Results

During differentiation, C2C12 murine myoblasts shift from a fusiform or star-shaped morphology to elongated confluent cells, eventually originating long, multinucleated myotubes (Burattini et al. 2004). Treatment with TNF $\alpha$  exerted a cytotoxic effect (Fig. 1A; Fig. S1), and reduced the expression of fast-type myosin heavy-chain in differentiated myotubes (Li et al. 1998; Li and Reid 2000; Fig. 1A). As expected, the DNA-binding activity of NF- $\kappa$ B, a well-known mediator of TNF $\alpha$  action, also significantly increased following TNF $\alpha$  challenge (Fernandez-Celemin et al. 2002; Fig. 1B). Confirming previous

observations (Li et al. 2005), TNF $\alpha$  significantly increased the mRNA levels of the muscle-specific ubiquitin ligase atrogen-1 after 2, 4, and 6 h (Fig. 1C), but not after 24 h treatment ( $C = 0.59 \pm 0.067$ , TNF $\alpha = 0.65 \pm 0.016$ ; data expressed as arbitrary densitometric units,  $n = 3$  for each group). The Ca<sup>2+</sup>-dependent proteolytic system also appeared activated, as suggested by increased levels of the  $\sim 80$  kDa calpain subunit (active calpain) in myotubes after exposure to TNF $\alpha$  for 2, 4, 6, and 24 h (Fig. 2).

In order to understand if TNF $\alpha$  may interfere with myostatin expression and activity in muscle cells, myostatin signaling was investigated in C2C12 myotubes exposed to the cytokine for 24 h. While follistatin was not modified by TNF $\alpha$ , myostatin abundance was significantly increased (Fig. 3a). Consistently, the DNA-binding activity of SMAD was increased compared to controls (Fig. 3b).

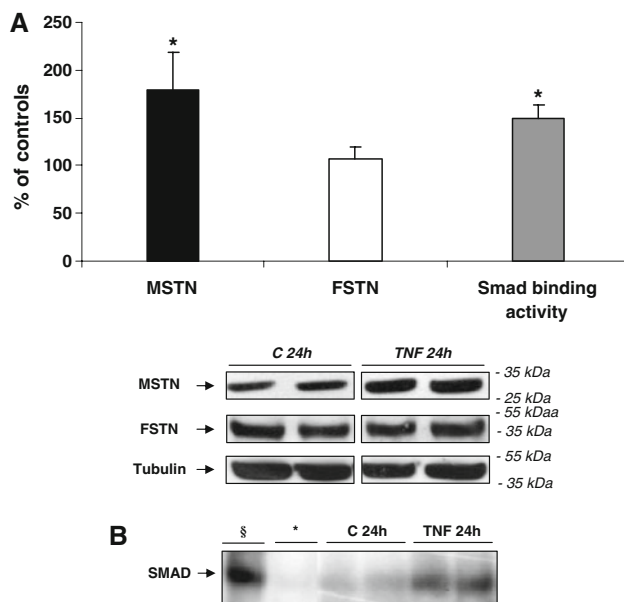
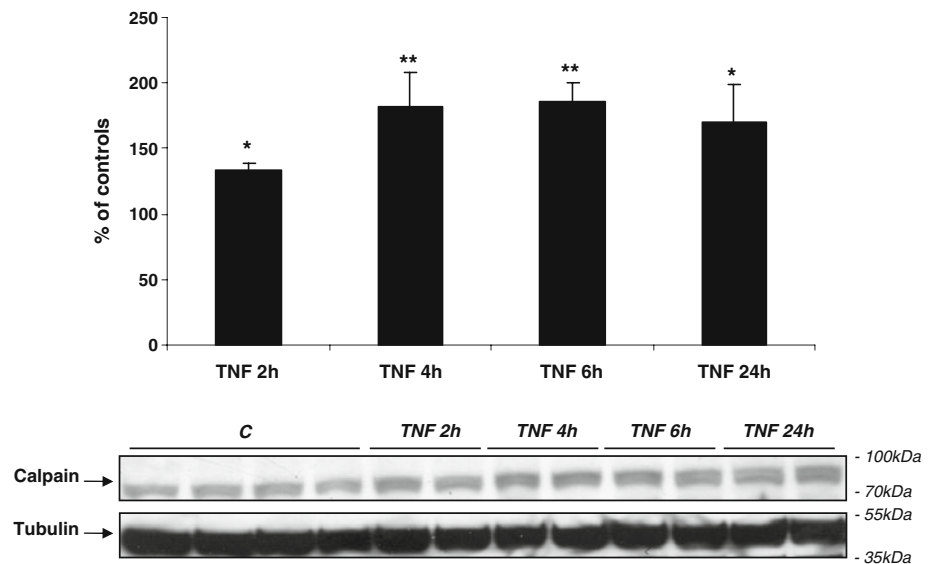
To assess whether amino acid supplementation of C2C12 myotubes could both reduce the hypercatabolic state and prevent muscle myostatin upregulation induced by TNF $\alpha$ , C2C12 myoblasts have been completely differentiated in glutamine or leucine-enriched medium. No difference in cell morphology could be observed once differentiation was completed in the presence of glutamine



**Fig. 1** Effects of TNF- $\alpha$  treatment (24 h) on C2C12 myotubes. **A** Morphological analysis. Phase contrast microscopy (panels a, e) and DAPI staining (panels b, f); MyHC expression (panels c, g). Merged pictures are represented in panels d and h. Bars 100  $\mu$ m. **B** State of activation of NF- $\kappa$ B in C2C12 myotubes exposed to TNF $\alpha$  for 24 h. EMSA analysis (representative pattern) indicating the

DNA-binding activity of NF- $\alpha$ B; hash positive control (HeLa cells), asterisk control sample incubated with excess cold oligonucleotide (specific competition). **C** RT-PCR representative pattern for atrogen-1 gene expression in C2C12 myotubes, controls (C) and treated with TNF- $\alpha$  for 2, 4, and 6 h

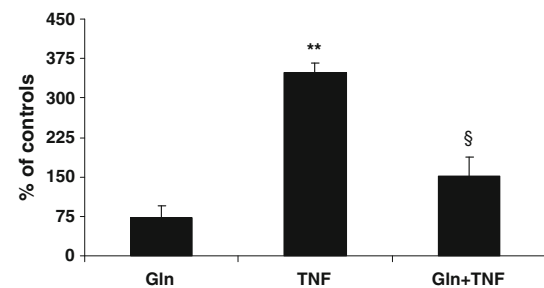
**Fig. 2** Calpain expression in TNF- $\alpha$ -treated C2C12 myotubes. Calpain (~80 kDa active subunit) protein levels and representative western blotting in C2C12 myotubes exposed to TNF- $\alpha$  for 2, 4, 6, 24 h. Data (means  $\pm$  SD;  $n = 3$ ) are expressed as percentage of controls (100%). Significance of the differences: \* $p < 0.05$ , \*\* $p < 0.01$  versus controls



**Fig. 3** Myostatin and follistatin expression (a), and SMAD DNA-binding activity (b) in C2C12 myotubes treated with TNF- $\alpha$  for 24 h. Representative western blotting for myostatin and follistatin levels, and EMSA for SMAD DNA-binding activity. Data (means  $\pm$  SD;  $n = 3$ , from 3 independent experiments) expressed as percentage of controls; hash positive control (HeLa cells), asterisk control sample incubated in the presence of an excess cold oligonucleotide (specific competition). Significance of the differences: \* $p < 0.05$  versus controls

or leucine excess. When TNF $\alpha$  is added to glutamine supplemented cultures, myotube reduction in size appears less marked than in the absence of glutamine (data not shown).

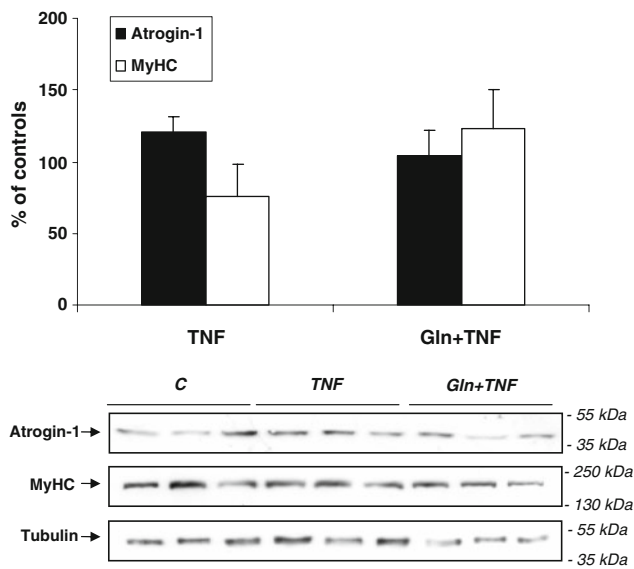
The increase in calpain enzymatic activity after 24 h TNF $\alpha$  treatment was significantly reversed by glutamine (Fig. 4), though not by leucine supplementation



**Fig. 4** Calpain enzymatic activity in C2C12 cells differentiated in the presence of excess glutamine (Gln), treated or not with TNF- $\alpha$  for 24 h. Data (means  $\pm$  SD;  $n = 3$ , from 3 independent experiments) are expressed as percentage of controls (100%). Significance of the differences: \* $p < 0.05$ , \*\* $p < 0.01$  versus controls; § $p < 0.05$  versus TNF

(TNF $\alpha = 1.02 \times 10^{-3} \pm 1.03 \times 10^{-4}$ , TNF $\alpha$ +Gln =  $6.94 \times 10^{-4} \pm 1.73 \times 10^{-4}$ , data expressed as nkatal/mg,  $n = 3$  for each group). The conspicuous hyperexpression of atrogen-1 mRNA observed after 6 h TNF $\alpha$  treatment (see Fig. 1C) was paralleled by a modestly increased protein abundance, that was reduced, although without reaching significance, by glutamine supplementation (Fig. 5). By contrast, atrogen-1 expression was not modified by leucine treatment (TNF $\alpha = 2.45 \pm 0.04$ , TNF $\alpha$ +Leu =  $2.00 \pm 0.29$ , data expressed as arbitrary densitometric units,  $n = 3$  for each group). Finally, glutamine supplementation also appeared to prevent the reduction of myosin-heavy-chain induced by 6 h TNF $\alpha$  treatment (Fig. 5).

Previous studies showed that both glucocorticoid-induced muscle wasting and myostatin upregulation decreased when dexamethasone-treated rats were fed a glutamine-enriched diet (Ma et al. 2003; Salehian et al. 2006). In this regard, we investigated whether TNF $\alpha$ -induced hyperexpression of myostatin could be counteracted by glutamine



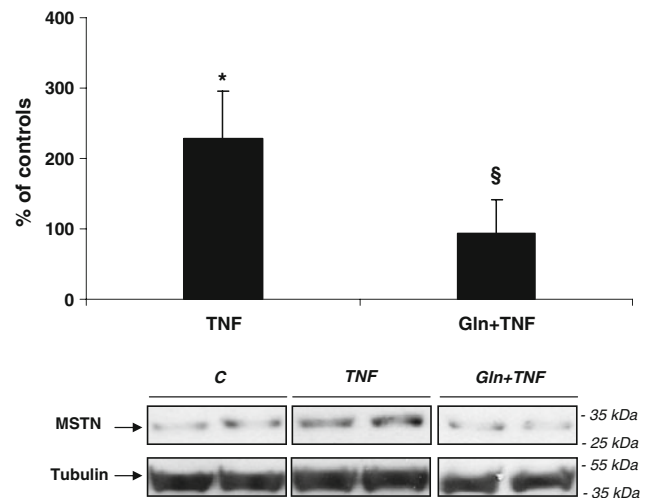
**Fig. 5** Atrogin-1 and MyHC protein levels in C2C12 cells differentiated in the presence of glutamine supplementation, treated or not with TNF- $\alpha$  for 6–24 h. Data (means  $\pm$  SD;  $n = 3$ , from 3 independent experiments) are expressed as percentage of controls (100%)

supplementation. The data reported in Fig. 6 show that TNF $\alpha$ -dependent myostatin upregulation was significantly reduced in excess glutamine-differentiated myotubes, while high glutamine alone did not significantly affect myostatin basal levels ( $C = 0.67 \pm 0.31$ , Gln =  $0.87 \pm 0.32$ , data expressed as arbitrary densitometric units,  $n = 3$  for each group).

## Discussion

The present study shows that hyperactivation of both the myostatin-dependent signaling and the intracellular proteolytic machinery induced in C2C12 myotubes by TNF $\alpha$  exposure can be reversed by glutamine supplementation.

The occurrence of enhanced protein breakdown in TNF $\alpha$ -treated C2C12 myotubes is demonstrated by the increased calpain enzymatic activity and is suggested by the early overexpression of atrogin-1. This is conceivable also in view of both the reduced myosin heavy-chain levels and the increased NF- $\kappa$ B DNA-binding activity (see Li et al. 1998; Li and Reid 2000; Fernandez-Celemin et al. 2002; Cai et al. 2004). The enhancement of atrogin-1 expression induced by TNF $\alpha$ , both in myocyte cultures and in the skeletal muscle, has been already reported by previous studies (Li et al. 2003, 2005; Frost and Lang 2007). In the last few years, there is evidence showing that atrogin-1 expression is regulated by the IGF-1/Akt/FoxO axis. However, although TNF $\alpha$  treatment of C2C12 myotubes results in significantly decreased expression of IGF-1



**Fig. 6** Myostatin protein levels in C2C12 cells differentiated in the presence of excess glutamine (Gln), treated or untreated with TNF- $\alpha$  for 24 h. Data (means  $\pm$  SD;  $n = 3$ , from 3 independent experiments) are expressed as percentage of controls (100%). Significance of the differences: \* $p < 0.05$  versus controls; § $p < 0.05$  versus TNF- $\alpha$

mRNA ( $C = 0.54 \pm 0.06$ , TNF $\alpha$  24 h =  $0.37 \pm 0.02$ ,  $p = 0.016$ ,  $n = 3$ , arbitrary densitometric units), the levels of phosphorylated (active) Akt remain comparable to control values ( $C = 1.55 \pm 0.51$ , TNF $\alpha$  24 h =  $1.27 \pm 0.32$ ,  $n = 3$ , arbitrary densitometric units). These results suggest that, at least in the model system used in the present study, atrogin-1 hyperexpression does not rely on down-regulation of the Akt/FoxO signaling. This is in line with a previous report showing that IGF-1 supplementation of TNF $\alpha$ -treated myotubes is unable to restore normal atrogin-1 levels (Moylan et al. 2008), and also with the observation that muscle wasting and atrogin-1 hyperexpression in experimental cancer cachexia are not associated with down-regulation of the IGF-1 signaling pathway, despite reduced IGF-1 levels (Costelli et al. 2006; Penna et al. 2010). By contrast, the MAPK/ERK pathway seems to play a role in the hyperexpression of atrogin-1, both in TNF $\alpha$ -treated C2C12 myotubes and in the skeletal muscle of tumor-bearing rats (Penna et al., submitted for publication).

As far as we know, this is the first study reporting that the  $\text{Ca}^{2+}$ -dependent proteolytic system is activated by TNF $\alpha$  in C2C12 myotubes. This result is consistent with a previous report showing that the increased calpain enzymatic activity in the skeletal muscle of tumor-bearing rats can be effectively prevented by treatment with pentoxifylline, an inhibitor of TNF $\alpha$  synthesis (Costelli et al. 2002). Quite recently calpain inhibition has been reported to reduce TNF $\alpha$ -induced neutrophil recruitment and activation (Wiemer et al. 2010). Consistently, LPS-induced myocardial alterations can be prevented by overexpression of calpastatin, the physiological inhibitor of calpain, by

transfection of calpain-1 siRNA, or by various pharmacological calpain inhibitors (Li et al. 2009). On the whole, these observations suggest that inhibition of calpain may be used as an approach to limit TNF $\alpha$ -induced inflammatory responses.

While the involvement of cytokines in the onset of muscle protein hypercatabolism is largely recognized (reviewed in Costelli and Baccino 2003; Argilés et al. 2009), little is known about the specific targets on which these mediators impinge to activate the intracellular proteolytic systems.

In the last few years myostatin/GDF-8 has been proposed as a negative regulator of skeletal muscle mass. Loss of function mutations of myostatin have been detected in sheep and cattle characterized by the so-called 'double-muscle' phenotype, and adult mice in which the myostatin gene has been disrupted showed a marked muscle hypertrophy compared to control littermates (McPherron et al. 1997; Clop et al. 2006). Myostatin has been found to be overexpressed in various conditions characterized by muscle atrophy, such as aging, disuse, sepsis, amyotrophic lateral sclerosis, dystrophy and cancer (Lecker et al. 1999; Bogdanovich et al. 2002; Zimmers et al. 2002; Holzbaur et al. 2006; Costelli et al. 2008; Liu et al. 2008; Bonetto et al. 2009).

We demonstrated that in rats bearing the AH-130 hepatoma muscle wasting and perturbations of the myostatin signaling pathway are both partially prevented by pharmacological inhibition of TNF $\alpha$  synthesis (Costelli et al. 2002, 2008). The present study shows that TNF $\alpha$  treatment of C2C12 myotubes causes changes in the myostatin pathway comparable to those observed in the AH-130 hosts: both myostatin expression and bioactivity are increased by exposure to the cytokine. Enhanced myostatin expression in TNF $\alpha$ -treated myotubes has also been recently reported (Lenk et al. 2009). The role played by TNF $\alpha$  in mediating myotube atrophy, likely through enhancement of myostatin expression, is further supported by the observation that follistatin hyperexpressing myotubes are resistant to the catabolic effects of the cytokine (Penna et al., submitted for publication).

The occurrence of a direct correlation between myostatin and protein metabolism has not yet been demonstrated. McFarlane et al. (2006) show that muscle depletion induced in mice by myostatin hyperexpression is associated with upregulation of atrogen-1. On the other side, glucocorticoid administration to mice knocked-out for myostatin does not result in increased levels of both atrogen-1 or MuRF1 (Gilson et al. 2007). Consistent with these reports, the results shown in the present study further support the hypothesis that a link likely occurs between protein degradation machinery and myostatin-dependent signaling pathway.

Muscle protein wasting represents a prominent complication in the management of patients affected by chronic pathologies, often resulting in increased morbidity and mortality rates, less benefit from therapies, and worsening of the quality of life. From this point of view the search for appropriate therapeutical strategies should be given a high priority. In this regard, amino acid supplementation is long known for its effectiveness in both improving muscle mass and preventing protein depletion (Dillon et al. 2009). Indeed, a group of amino acids in the diet, normally considered as non-essential, has been suggested to become essential in several disease states. This is the case of glutamine, glutamate, arginine, ornithine, citrulline and proline, that are metabolically related and fall within a common biosynthetic family tree derived from  $\alpha$ -ketoglutarate (Robinson et al. 1999; Baracos 2001).

Prolonged amino acid supplementation has been reported to decrease skeletal muscle protein breakdown via selective inhibition of both lysosomal and Ca<sup>2+</sup>-dependent proteolysis in young rats, as well as proteasome activities in adult rats (Capel et al. 2009). Moreover, administration of an amino acid mixture (containing, among others, leucine, valine, methionine and cysteine; 8 g/day for 16 months) effectively reduces circulating TNF $\alpha$  levels and increases plasmatic IGF-1, contributing to significantly improve muscle mass in geriatric patients with sarcopenia (Solerte et al. 2008). Quite recently, glutamine administration to LPS-treated mice has been demonstrated to preserve muscle force without modifying circulating TNF $\alpha$ , suggesting that glutamine target(s) is/are downstream of cytokine production (Meador and Huey 2009). Finally, Salehian et al. (2006) reported that in glucocorticoid-treated animals both muscle wasting and myostatin hyperexpression can be prevented by administration of glutamine. Consistently, enrichment of culture medium with this amino acid results in restoration of normal myostatin expression in dexamethasone-treated C2C12 myotubes (Salehian et al. 2006).

The present study shows that glutamine supplementation restores physiological levels of myostatin expression in TNF $\alpha$ -treated C2C12 myotubes. Of interest, myostatin modulations are associated with normalization of both Ca<sup>2+</sup>-dependent proteolysis and atrogen-1 expression, further supporting the occurrence of a relationship between myostatin and intracellular proteolysis. The mechanism by which glutamine can exert such effects, however, remains to be elucidated.

Our results show that leucine supplementation does not interfere with the modulations of proteolytic systems induced by TNF $\alpha$ . This is in contrast with recent works reporting that branched-chain amino acids, and especially leucine, suppress atrogen-1 mRNA expression via mTOR pathway in C2C12 myocytes (Talvas et al. 2006; Du et al. 2007; Herningtyas et al. 2008). The different experimental



design can account for the discrepancy with the data reported in the present study. Indeed, in the studies reported above, myotubes were initially deprived of amino acids, thus likely inducing a complex form of cell death with hallmarks of both apoptosis and autophagy, and soon later exposed to a medium containing leucine, which is a well-known inhibitor of the autophagic process (Martinet et al. 2005).

In conclusion, the present study indicates that TNF $\alpha$  plays a role in increasing both myostatin expression and bioactivity, thus supporting the hypothesis that this cytokine could exert its pro-catabolic action via this pathway as well. This view, however, is questioned by previous observations performed on rats bearing the AH-130 hepatoma, where prevention of muscle wasting and myostatin upregulation by pentoxifylline is not associated with restoration of normal atrogin-1 mRNA levels (Costelli et al. 2008). In this regard, further studies are needed to clarify whether TNF $\alpha$ -induced modulations of the myostatin pathway follow rather than precede the activation of muscle protein breakdown. In addition, the results shown in the present study improve the knowledge about the mechanisms involved in the beneficial effect exerted by glutamine on muscle wasting, suggesting the myostatin signaling pathway as a possible target of nutritional interventions based on amino acid supplementation.

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