Effect of denervation on the regulation of mitochondrial transcription factor A expression in skeletal muscle

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Tryon LD, Crilly MJ, Hood DA. Effect of denervation on the regulation of mitochondrial transcription factor A (Tfam) expression in skeletal muscle. Am J Physiol Cell Physiol 309: C228–C238, 2015. First published June 10, 2015; doi:10.1152/ajpcell.00266.2014.—The purpose of this study was to determine how the expression of mitochondrial transcription factor A (Tfam), a protein that governs mitochondrial DNA (mtDNA) transcription and replication, is regulated during a state of reduced organellar content imposed by muscle disuse. We measured Tfam expression at 8 h, 16 h, 24 h, 3 days, or 7 days following denervation and hypothesized that decreases in Tfam expression would precede mitochondrial loss. Muscle mass was lowered by 13% and 38% at 3 and 7 days postdenervation, while cytochrome c oxidase activity fell by 33% and 39% at the same time points. Tfam promoter activation in vivo was reduced by 30–65% between 8 h and 3 days of denervation, while Tfam transcript half-life was increased following 8–24 h of denervation. Protein expression of RNA-binding proteins that promote mRNA degradation (CUG repeat-binding protein and K homology splicing regulator protein) was elevated at 3 and 7 days of denervation. Tfam localization within subsarcolemmal mitochondria was reduced after 3 and 7 days of denervation and was associated with suppression of the cytochrome c oxidase type I transcript at 3 days, indicating that denervation impairs both mitochondrial Tfam import and mtDNA transcription during an early period following denervation. These data suggest that putative signals downregulate Tfam transcription during the earliest stages following denervation but are counteracted by increases in Tfam mRNA stability. Import of Tfam into the mitochondrion seems to be the most critical point of regulation of this protein during the early onset of denervation, an impairment of which is coincident with the loss of mitochondria during muscle disuse.

CHRONIC MUSCLE DISUSE, such as that brought about by denervation, is a potent inducer of muscle atrophy (1, 48, 54). This phenomenon arises as a result of the shift in the balance between protein synthesis and degradation, favoring muscle catabolism (3, 18), in addition to the activation of pathways mediating macroautophagy (39, 40, 58). Concomitant with the reduction in muscle fiber size, mitochondrial content is also diminished, which likely accounts for impairments in muscle endurance performance (16, 54).

The regulation of mitochondrial content has been well documented; it is primarily stimulated by the activity of the transcriptional coactivator peroxisome proliferator-activated receptor-γ coactivator-1α (PGC-1α) (21, 46). PGC-1α is capable of controlling the expression of a variety of aspects of mitochondrial biogenesis through the coactivation of key nuclear transcription factors, such as nuclear respiratory factors-1 and -2 (36), which in turn can promote the expression of mitochondrial transcription factor A (Tfam) (51). Mitochondrial biogenesis requires the coordinated expression of genes encoded within the nuclear and mitochondrial genomes (mtDNA). To properly orchestrate mitochondrial biogenesis, factors that promote the transcription and expression of mtDNA must be transcribed from the nuclear genome and imported into mitochondria. Tfam, along with mitochondrial transcription factor B (Tfb2m) and mitochondrial RNA polymerase (POLRMT) (47, 57), is a required component of the mitochondrial transcription machinery. Tfam is unique, in that it has the ability to bind to mtDNA and distort it into a U-turn-like structure, facilitating access of other accessory components to promote mtDNA transcription (37, 43). Beyond this, Tfam also has essential roles in the replication and compaction of mtDNA into nucleoid structures (14, 25).

The necessity of Tfam has been highlighted by Larsson et al. (30), who demonstrated that whole body homozygous Tfam ablation results in embryonic lethality, whereas viable heterozygous Tfam knockout mice display reductions in mtDNA levels and compromised electron transport chain function. Muscle-specific knockouts of Tfam display similar mitochondrial impairments (55). Conversely, the transient overexpression of Tfam is sufficient to induce mtDNA expression and mitochondrial mRNAs (34). Furthermore, increases in the expression and mitochondrial import of Tfam in response to contractile activity have been shown to precede increases in mitochondrial content, suggesting a crucial role for this protein in the regulation of contractile activity-induced mitochondrial biogenesis (20). These reports underscore the vital role of Tfam in mtDNA expression, as well as organellar function.

However, the significance of regulating Tfam expression during denervation-induced atrophy has not been fully explored. Previous work has documented that denervation-induced disuse reduces mitochondrial content quite rapidly, depleting the mitochondrial pool by up to 40% following 1 wk of denervation (1, 48). This is associated with considerable reductions in the expression of factors regulating mitochondrial biogenesis (1, 44, 45, 53), including PGC-1α and Tfam, along with an impairment of protein import into the mitochondrial matrix (48).

Thus the purpose of this study was to investigate the relationship between the expression of Tfam and mitochondrial content during denervation-induced disuse. We examined the expression of Tfam at the transcriptional and posttranscriptional levels during the first week of denervation, as this is the time frame in which the most rapid and substantial loss of mitochondrial content occurs. We hypothesized that a decline in Tfam content would precede reductions in mitochondrial content.
content as a result of a diminished drive for mitochondrial biogenesis.

MATERIALS AND METHODS

Animals and experimental design. Animal care and experimental procedures were approved by the York Animal Care Committee and were in accordance with the Canadian Council of Animal Care. Male Sprague-Dawley rats (300–400 g body wt; Charles River, St. Constant, QC, Canada) were randomly assigned to one of five time-course groups: 8 h, 16 h, 24 h, 3 days, or 7 days. Prior to denervation in a subset of animals, the tibialis anterior (TA) of both hindlimbs was electrotransfected with the rTfam-pGGL3 vector. At 4 days following electrotransfection, rats underwent surgery to induce unilateral hindlimb denervation while the contralateral hindlimb was sham-operated. At each of these time points, animals were euthanized and the TA muscles were excised from the denervated and contralateral, sham-operated limb. TA muscles from both limbs of these animals were used for a selection of biochemical analyses. In a separate set of experiments, a subset of male Sprague-Dawley rats was randomly assigned to one of three time-course groups: 24 h, 3 days, or 7 days. These animals were denervated as described below, and at each time point, animals were euthanized. The TA muscles from these animals were used to isolate subsarcolemmal (SS) mitochondrial and cytosolic fractions from freshly excised tissue, while the extensor digitorum longus (EDL) was fixed and frozen for cross-sectional area analyses.

Denervation surgery protocol. Rats were anesthetized using gas-eous isoflurane. The fast-twitch TA and EDL muscles were denervated by exposure of the left common peroneal nerve and transection of a 5-mm section. The contralateral hindlimb underwent the same procedure, whereby the right common peroneal nerve was exposed, but not transected. After administration of sterile ampicillin, the incision was sutured and closed with metal clips. The day of surgery represented day 0 of the time course. Animals were given amoxicillin in their drinking water [0.025% (wt/vol)] following the surgery. At the conclusion of the time course for each group, animals were anesthetized with ketamine-xylazine (0.2 ml/100 g body wt, ip), and sham-operated and denervated TA muscles were excised, clamped frozen in liquid nitrogen, and stored at −80°C. Muscle samples used for biochemical analyses were then pulverized at the temperature of liquid nitrogen, while samples used for cross-sectional analyses were prepared as described below.

Cross-sectional analyses and succinate dehydrogenase staining. EDL muscles from the sham-operated and denervated hindlimb were excised from the animal, mounted in Cryomatrix (Thermo Scientific), and frozen in isopentane at the temperature of liquid nitrogen. These muscles were then cryosectioned into 10-μm sections, transferred to/D926280°C. Muscle samples used for biochemical analyses were then pulverized at the temperature of liquid nitrogen, while samples used for cross-sectional analyses were prepared as described below.

Cytochrome c oxidase activity. Pulverized frozen muscle TA samples were diluted sevenfold (wt/vol) in 1× passive lysis buffer. Homogenates were sonicated on ice (3 times for 10 s each) and subsequently centrifuged at 16,100 g for 5 min at 4°C. After centrifugation, 20 μl of the supernate were used to assess pGL3 luciferase activity using a luminometer (Lumat LB9507). pGL3 luciferase values were corrected for electrotransfection efficiency by simultaneous assessment of pRL CMV Renilla luciferase activity. Protein concentrations were determined by the Bradford colorimetric protein assay.

In vitro cytosolic protein extraction. Frozen powders (50 mg) from sham-operated and denervated TA muscles were homogenized separately in 50 μl of sterile homogenization buffer (25% glycerol, 0.42 M NaCl, 1.5 mM MgCl2, 0.2 mM EDTA, 20 mM HEPES, pH 7.9, 0.5 mM 1,4-DTTC, 0.5 mM PMSF, and RNase-free water) at 30% power output three times for 10 s each. Homogenates were centrifuged at 5,000 g for 15 min at 4°C. The supernate was transferred to a sterile Eppendorf tube and further centrifuged at 15,000 g for 15 min at 4°C to produce mitochondria-free (S15) crude cytosolic fractions. Protein concentrations were determined by the Bradford colorimetric protein assay.

In vitro RNA isolation. Total RNA was isolated using TRIzol reagent (Life Technologies), whereby muscle tissue powders were derived from TA of the sham-operated or denervated animals (~100 mg tissue/ml TRI Reagent). RNA isolation was performed as previously described (11, 28). Briefly, RNA was precipitated overnight at −20°C with isopropanol and subsequently pelleted, washed, dried, and resuspended in sterile water. RNA concentration and purity were assessed using spectrophotometry, while RNA quality was affirmed through separation on a 1% agarose-formaldehyde gel for visualization of 28S and 18S RNA.

In vitro mRNA decay assay. Total RNA (35 μg) derived from TA muscle of Sprague-Dawley rats was combined with 20 μg of S15 cytosolic extracts derived from the denervated or control TA muscle of animals subjected to the time-course denervation protocol. To allow for assessment of the degradation of RNA within the incubated tubes as a percentage of the original RNA content, a tube containing...
35 μg of RNA and 5 μl of sterile homogenization buffer in a 100-μl reaction volume served as a baseline measure at time 0. This sample does not contain the cytosolic proteins, and it allowed us to determine the amount of RNA in the sample without the influence of cytosolic factors. Reaction volumes were set at 100 μl, and samples were incubated at 37°C for 15 or 45 min. At the completion of each incubation time point, phenol was added to each sample, which was shaken vigorously to halt mRNA degradation. Total RNA was then reisolated using a phenol-chloroform-isomyl alcohol extraction procedure as previously described (28). The reisolated RNA was pelleted, washed, dried, and resuspended in sterile water. RNA concentration and purity were determined via spectrophotometry.

Reverse transcription-polymerase chain reaction. For the purpose of assessment of mRNA decay kinetics, cDNA was reverse-transcribed from 1.5 μg of total RNA, which was isolated following the in vitro decay assay, using SuperScript III reverse transcriptase in a 20-μl reaction. Subsequently, cDNA was amplified by semiquantitative polymerase chain reaction (PCR) using GoTaq Flexi DNA polymerase (Promega) with the required reagents and sequence-specific sense and antisense primers in a 50-μl reaction. Primer sequences and PCR cycle count for Tfam and ribosomal protein S12 (Rps12) are listed in Table 1. PCR products (40 μl) were visualized on ethidium bromide stained 1.8% agarose gels under UV light and quantified using Sigma Scan Pro (v.5) software. For use in real-time PCR, oligonucleotide primers were designed using sequences from GenBank and Primer3 (v.0.4.0) software (MIT, Cambridge, MA), and primer specificity was confirmed using OligoAnalyzer 3.1 (Integrated DNA Technologies). Real-time PCR primer sequences for Tfam, COX I, Rps12, and cytoskeletal protein β-actin (Actb) transcripts are also listed in Table 1.

Real-time PCR. Gene expression was quantified in a 96-well plate using the StepOnePlus real-time PCR system (Applied Biosystems), along with SYBR Green chemistry (PerfeCTa SYBR Green SuperMix, ROX, Quanta BioSciences). Each well contained SYBR Green SuperMix forward and reverse primers (20 mM) and 100 ng of cDNA or total DNA (diluted in diethylpyrocarbonate-treated water), resulting in a final reaction volume of 25 μl per well. The PCR program consisted of a holding stage (95°C for 10 min), followed by 40 cycles of annealing (60°C for 1 min) and extension (95°C for 15 s) and a final melting stage (95°C for 15 s, 60°C for 1 min, 95°C for 15 s). Samples were tested in duplicates to ensure accuracy. Analyses of melt curves on ethidium bromide-stained 1.8% agarose gels under UV light and quantification of mtDNA and nuclear DNA (nDNA), whereby the CT value of the sham-operated tissue was then subtracted from the CT value of the denervated tissue [ΔCT = CT(denervated) - CT(sham-operated)]. Results are reported as fold changes using the ΔΔCT method, calculated as 2^{-ΔΔCT}.

Table 1. PCR primers

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Tfam, mitochondrial transcription factor A; S12, ribosomal protein 12 (Rps12); COX I, cytochrome c oxidase subunit I; COX II, cytochrome c oxidase subunit II; D-loop region, noncoding regulatory region of the mitochondrial genome; β-actin, cytoskeletal protein β-actin; bp, base pairs.
Jasmin (University of Ottawa). After incubation, blots were washed in 1× TBST (3 times for 5 min each) to remove excess primary antibody and incubated with the appropriate secondary antibody coupled to horseradish peroxidase at room temperature for 1 h. Membranes were washed again with 1× TBST to remove excess secondary antibody, and antibody-bound protein was revealed by the enhanced chemiluminescence method. Films were scanned and analyzed using Car-estream Molecular Imaging software standard edition v.5.4.2. To control for loading, protein quantifications were corrected with aci-culin or porin immunoblotting or Ponceau staining where noted. There was no effect of time or denervation on the loading controls.

Statistical analyses. Data were produced and analyzed with Graph-Pad 4.0 software, and values are means ± SE. Student’s paired t-test was employed to assess differences between conditions. The nonlinear regression equation $50 = 100e^{-kx}$ (where $k$ is the measured rate of decay) was used to calculate mRNA half-lives. A two-way ANOVA was performed to determine differences in Tfam half-life.

RESULTS

Effect of denervation on muscle mass, muscle fiber cross-sectional area, and mitochondrial content. Denervation of the TA muscle did not influence muscle mass within the first 24 h; however, significant reductions in muscle mass of 13% and 38% were observed after 3 and 7 days of denervation compared with the contralateral, sham-operated hindlimb ($P < 0.05$; Fig. 1A). To ensure that the lack of change in muscle mass within the first 24 h of denervation was not masked by local tissue inflammation and edema, we compared the wet and dry tissue masses of the TA muscle within this time period. There was no difference in the ratio of wet mass to dry mass of this muscle, confirming that tissue edema did not confound our measures of muscle mass during the period immediately following denervation (Fig. 1B). We also assessed the effect of denervation on

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Fig. 1. Denervation (DEN) decreases hindlimb muscle mass and cross-sectional area (CSA). A: tibialis anterior (TA) muscle mass corrected for body mass (BM, $n = 5–7$ per time point). B: TA wet weight corrected for dry weight ($n = 3$ per time point). C: extensor digitorum longus (EDL) muscle mass corrected for body mass ($n = 4$ per time point). D: succinate dehydrogenase staining of sham-operated and denervated EDL muscles at 24 h, 3 days, and 7 days of denervation. E: fiber size distributions from sham-operated, 3-day-denervated, and 7-day-denervated EDL muscles. CSA data for sham-operated hindlimbs are pooled results of all sham-operated muscles analyzed ($n = 4$ per time point). *$P < 0.05$ vs. sham at the same time point. Values are means ± SE.

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the muscle mass and cross-sectional area of the EDL. Denervation reduced the mass of the EDL by 4 and 30% after 3 and 7 days, respectively (Fig. 1C). Individual fiber cross-sectional area of the EDL was also reduced following 3 or 7 days of denervation (Fig. 1, D and E), illustrated by the leftward shift in the fiber size frequency distributions with continued denervation (Fig. 1E). These data verify that our denervation paradigm was sufficient to induce a reduction in muscle mass and cross-sectional area.

Effect of denervation on mitochondrial content and expression of nuclear- and mitochondrial-encoded mitochondrial proteins. To assess a time course of the reduction in mitochondrial content with denervation, we measured COX activity, a common marker indicative of the mitochondrial content of a tissue. COX activity declined by 33 and 39% after 3 and 7 days of denervation, respectively (Fig. 2A). We also measured the expression of mitochondrially encoded COX subunits in isolated SS mitochondrial fractions. In particular, the protein expression of COX I and COX II was reduced by 36 and 72% and by 55 and 85% by 3 and 7 days of denervation, respectively (Fig. 2, B and C). In a similar fashion, denervation lowered expression of the nuclear-encoded COX IV protein by 33 and 72% at 3 and 7 days of denervation (Fig. 2D).

Effect of denervation on mtDNA copy number and mtDNA transcription. As a corollary measure of mitochondrial content, we measured relative mtDNA copy number by real-time PCR, which was determined as the ratio of mtDNA to nDNA. We used primers for the mtDNA D-loop region as a marker of mtDNA and the cytoskeletal protein β-actin (Actb) as a measure of nDNA to quantify the relative abundance of mtDNA and nDNA. After 3 and 7 days of denervation, the ratio of mtDNA to nDNA was reduced by 20 and 43%, respectively (Fig. 3A). Similar reductions in the ratio of mtDNA to nDNA were observed when primers for the COX I- or COX II-encoding regions of mtDNA were used in place of the D-loop region as a mtDNA marker to determine relative mtDNA copy number (data not shown). To determine whether denervation may have also had an impact on mtDNA transcription, we measured the mRNA content of the mtDNA-encoded COX I as an indirect index of mtDNA transcription. Denervation significantly reduced COX I mRNA by 36 and 25% after 3 and 7 days of denervation, respectively (P < 0.05; Fig. 3B). We subsequently corrected these values to the mtDNA copy num-

Fig. 2. Denervation lowers mitochondrial content and reduces expression of cytochrome c oxidase (COX) subunits in isolated mitochondria. A: TA COX activity in response 8 h, 16 h, 24 h, 3 days, and 7 days of denervation (n = 5 per time point). B–D: representative Western blots of mitochondrial DNA-encoded proteins COX I (B) and COX II (C), as well as the nuclear DNA-encoded protein COX IV (D) in isolated subsarcomemal mitochondria from sham-operated (S) or denervated (D) muscle (n = 4 per time point for all experiments) *P < 0.05 vs. sham at the same time point. Values are means ± SE.
Values are means previously showed that the import of the mitochondrial matrix-corrected for mtDNA copy number. *P < 0.05; Fig. 3).

If this ratio increased by 35% after 7 days of denervation (P < 0.05), the mtDNA copy number by 22% after 3 days of denervation, but intriguingly, significantly reduced the ratio of COX I mRNA to mtDNA copy number (Fig. 3A). Denervation signifi-

can classify any condition.

Effect of denervation on Tfam intracellular localization. We previously showed that the import of the mitochondrial matrix-destined protein octamer-binding transcription factor is diminished in response to denervation (48). To further test our hypothesis that denervation reduces matrix-destined protein import, we measured the protein abundance of Tfam, a fundamental component of machinery required to transcribe mtDNA, in isolated SS mitochondria, as well as in the cytosolic fractions of the same muscles (Fig. 4A). Our Tfam antibody detects two bands, a 27-kDa, full-length precursor Tfam, which was present exclusively in the cytosol, and a 24-kDa mature Tfam, which was localized in mitochondria. The difference in molecular weight is accounted for by the proteolytic removal of the mitochondrial targeting sequence during protein import (49). In line with our previous measurements, SS mitochondrial Tfam content was reduced by 63 and 67% after 3 and 7 days of denervation, respectively (Fig. 4A), a decrease that was approximately twofold greater than the decline in overall mitochondrial content (Fig. 2A).

Effect of denervation on Tfam transcriptional activation, mRNA content, and stability. Given the well-described role for Tfam in the expression of mtDNA-encoded transcripts, mtDNA copy number, and, consequently, mitochondrial function, we set out to assess the regulation of Tfam expression in response to denervation at the transcriptional and posttranscriptional levels. To measure the transcriptional activation of the Tfam promoter, we electrotransfected a 1.1-kb rat Tfam promoter-luciferase reporter into the TA prior to denervation. Activity of the promoter was reduced by 30–65% between 8 h and 3 days of denervation but was not significantly different from the contralateral, sham-operated TA after 7 days of denervation (Fig. 4B). Tfam mRNA was not different between denervated and sham-operated muscles between 8 h and 3 days of denervation but was increased 1.9-fold after 7 days of denervation (Fig. 4C). To resolve the incongruence between Tfam transcription and transcript levels, we also measured the stability of Tfam mRNA using an established in vitro cell-free mRNA decay assay (11, 28). Tfam mRNA was stabilized during short-term denervation, as transcript half-life was enhanced 1.8-fold after 8 h (P < 0.05) and 3-fold after 24 h (P = 0.08) of denervation (Fig. 4D). However, after 7 days of denervation, Tfam transcript stability was decreased by ~40% compared with its half-life in the sham-operated muscle (P < 0.05; Fig. 4D). Thus, despite the early reduction in Tfam transcriptional activity following denervation, mRNA content is maintained at a constant level as stability is increased during the same time period.

Expression of RNA-binding proteins during denervation. To gain further insight into the mechanisms mediating Tfam mRNA half-life during denervation, we assessed the expression of several RNA-binding proteins (RBPs) that have been implicated in the regulation of mRNA stability. In whole muscle protein extracts, no effect of denervation was observed on expression of HuR, a protein that promotes the stability and translation of target mRNAs (29) (Fig. 5A). Expression of CUGBP1, an mRNA-destabilizing protein that can interact with GC-, GU-, and AU-rich elements (36, 42), was elevated 1.4-, 1.9-, and 4.3-fold by 24 h, 3 days, and 7 days following denervation, respectively (Fig. 5B). KSRP, a protein that has role in the modulation of AU-rich element-containing mRNAs (19), was increased by 2.1- and 2.8-fold at 3 and 7 days postdenervation, respectively (Fig. 5C).

![Graph](https://via.placeholder.com/150)

Fig. 3. Denervation reduces mitochondrial DNA (mtDNA) copy number and mtDNA transcript expression. A: relative mtDNA copy number in TA muscle, calculated as ratio of mtDNA to nuclear DNA (n = 5 per time point). Threshold cycle (Ct) values from quantitative PCR of the mtDNA D-loop region were normalized to nuclear DNA-encoded cytoskeletal protein β-actin, which was unchanged across all conditions. B: as an indirect index of mtDNA transcription, mRNA content of mtDNA-encoded COX I was measured using quantitative PCR (n = 5–6 per time point). C: cellular COX I transcript levels corrected for mtDNA copy number. *P < 0.05 vs. sham at the same time point. Values are means ± SE.
DISCUSSION

It is well documented that chronic denervation-induced muscle atrophy is associated with a concomitant reduction in muscle mitochondrial content (1, 48, 54). Interestingly, this decrease in mitochondrial content appears to proceed in two phases: a rapid, substantial reduction that occurs during the first week subsequent to denervation followed by a slower, more gradual decline in the weeks that follow (1, 54). Previous work has highlighted the reduction in expression of factors implicated in mitochondrial biogenesis with prolonged muscle denervation (1, 44, 53). However, given the extensive decrease in muscle mitochondrial content during the early stages, we
wished to determine if this was a by-product of a diminished drive for mitochondrial biogenesis. To do so, we examined the impact of denervation on the expression of Tfam, an essential nuclear-encoded mitochondrial transcription factor noted for its role in controlling mitochondrial DNA copy number, transcription, and compaction (13, 26, 34, 55). Thus the primary purposes of this study were to investigate the influence of short-term denervation-induced disuse on the control of various levels of Tfam expression and to determine if the large reduction in mitochondrial content could be attributed to alterations in the regulation of this transcription factor. We hypothesized that Tfam transcriptional activity, mRNA, and intramitochondrial protein content would decline and that these changes would precede the lessening of mitochondrial content.

Our first goal was to determine how rapidly and to what extent muscle mass and mitochondrial content were reduced during the very early stages of denervation. Our data illustrate that muscle mass of the TA (Fig. 1A) and EDL (Fig. 1, C–E) was reduced as soon as 3 days following denervation and declined further thereafter. To ensure that muscle atrophy at the earliest time points following denervation was not masked by inflammation and edema, we determined that there were no differences in the water content of the muscles from the sham-operated or denervated hindlimbs (Fig. 1B). Furthermore, we confirmed that the reduction in muscle mass was indeed a consequence of the reduction in muscle fiber size, a hallmark of atrophy, by quantifying fiber cross-sectional area (Fig. 1, D and E). The leftward shift in the fiber size distribution (Fig. 1E) with increasing time of denervation indicates that this was certainly the case.

The reduction in muscle mass was paralleled by a decline in COX activity, a common index of mitochondrial content, after 3 and 7 days of denervation (Fig. 2A). This change occurred in concert with a reduced expression of mitochondrial- and nuclear-encoded mitochondrial proteins. Specifically, we assessed the protein content of three subunits of the COX holoenzyme, COX I, COX II, and COX IV, in isolated SS mitochondria. Both mitochondrially encoded COX I and COX II proteins were reduced within the organelle following 3 and 7 days of denervation (Fig. 2, B and C). Similarly, nuclear-encoded COX IV was coordinately reduced (Fig. 2D), an effect that is likely mediated by the reduction in PGC-1α with denervation (1, 5, 22, 45, 53), a potent inducer of COX IV expression (32, 56). Additionally, the diminished expression of these subunits may also be linked to the impairment in mitochondrial respiration during muscle disuse (1, 38, 40, 48).

In parallel with the reduction in COX activity, we observed a decrease in mtDNA copy number, another marker of mitochondrial content, after 3 and 7 days of denervation (Fig. 3A). Additionally, COX I transcript levels were attenuated at these same time points (Fig. 3B), providing evidence for a reduction in mtDNA transcription, which contributes to the reduced protein expression of mtDNA-encoded COX subunits (Fig. 2, B and C). To examine whether the changes in COX I transcript levels were a by-product of the reduction in mtDNA copy number, we normalized these values to the mtDNA copy number at each time point of denervation (Fig. 3C). After 3 days of denervation, the ratio of COX I transcript to mtDNA copy number was reduced, suggesting that, at this time point, the impairment in mtDNA transcription was greater than the reduction in mtDNA copy number (Fig. 3C). To our surprise, this trend was reversed by 7 days of denervation, suggesting that the denervation-induced time-dependent decrease in mtDNA transcripts is due to a combination of reduced transcription and diminished mtDNA copy number.

Since Tfam is important in the regulation of mtDNA transcription and copy number, we investigated the regulation of Tfam expression at the transcriptional, posttranscriptional, and posttranslational levels. We previously showed that, with 6 wk of denervation, total cellular Tfam protein levels are reduced by 60% (1). Additionally, the import of ornithine carbamoyltransferase, a mitochondrial matrix-destined protein, was decreased as early as 3 days following denervation (48). Thus we hypothesized that denervation would result in a reduction of Tfam within mitochondria. To test this, we examined the protein content of Tfam in isolated SS mitochondria, as import into the mitochondrial matrix is required for it to interact with
mtDNA. We chose to specifically investigate SS mitochondria, as this mitochondrial subpopulation has been shown to adapt to physiological stimuli with greater rapidity than the intermyofibrillar population (1, 4, 24, 48). In line with previous data, our current work reveals that intramitochondrial Tfam content was lowered in SS mitochondria as early as 3 days of denervation (Fig. 4A). This may provide a mechanism for the reduction in mtDNA copy number and COX I transcript levels at these same time points.

We then set out to examine the regulation of Tfam at the transcriptional and posttranscriptional levels to further evaluate the relationship between Tfam expression and mitochondrial content during changes in muscle activity. Interestingly, Tfam transcription in the TA muscle was reduced as early as 8 h following the denervation surgery and remained depressed for up to 3 days after removal of the neural stimulus (Fig. 4B). This provides evidence that factors interacting with the 1.1-kb proximal rat promoter of this gene are either less active in the induction or more active in the repression of the transcription of this gene and that this occurs well before the reduction of mitochondrial content. Unexpectedly, the mRNA content of Tfam was unaltered during this same time period (Fig. 4C), which exposed a dissociation between transcription and steady-state mRNA levels.

To evaluate this further, we utilized a cell-free in vitro decay assay that has been well described by our laboratory (11, 17, 28) to determine relative mRNA degradation rates between multiple divergent skeletal muscles. In this case, we sought to compare the degradation rate of Tfam mRNA between skeletal muscle that had been sham-operated or denervated. Our observations indicate that Tfam mRNA decay was attenuated at the early time points following denervation (Fig. 4D). This suggests that the lack of change in the steady-state Tfam mRNA could be accounted for by concomitant decreases in mRNA transcription, along with increases in mRNA stability. We are uncertain of the reason for the increase in mRNA content of Tfam following 7 days of denervation, but this may be due to a concomitant deficiency in the cell's capacity to translate the transcript. While we have not assessed the impact of denervation on translation in the current work, previous studies have suggested that skeletal muscle atrophy is associated with impairments in the initiation of translation (10, 27), as well as the diminished expression and activity of ribosomal components (23, 33, 35). We also previously documented the existence of tissue-specific mechanisms that control the stability of mitochondrial-associated mRNAs (9, 11, 28). The current work highlights the notion that, in addition to tissue-specific mechanisms, mRNA stability is also reliant on time-dependent factors following the onset of an adaptive stimulus (Fig. 4D). Interestingly, we previously noted an opposing change, that is, a reduction in mRNA stability in response to chronic muscle use (28), indicating that the influence of mRNA stability is also stimulus-dependent.

In an attempt to reveal possible mechanisms accounting for the different half-lives of the Tfam transcript between sham-operated and denervated muscles, we investigated factors that might contribute to the change in Tfam transcript stability. The stability of mRNAs is mediated primarily by sequence elements found in the 3′-untranslated regions (UTRs) of transcripts, most notably those rich in adenosine and uridine (AU-rich elements) and guanosine and uridine (GU-rich elements) (7, 52). RBPs bind to these elements and promote the stabilization or degradation of the target mRNAs. In preliminary analyses, we mapped the 3′-UTR of the rat Tfam transcript and identified multiple potential binding sites for several RBPs based on target consensus sequences (7, 19, 36, 41, 42). We chose to measure several RBPs that have been characterized in skeletal muscle to have a role in facilitating transcript stabilization, as is the case with HuR (15, 31), or in promoting transcript destabilization, such as CUGBP1 (31) and KSRP (2, 6).

Our results indicate that HuR expression remained unaltered over the denervation time course (Fig. 5A), while whole cell protein expression of CUGBP1 and KSRP was elevated with progressive denervation (Fig. 5, B and C). This suggests that the overall cellular expression of these factors may not control the alterations in stability at the early denervation time points. While not examined in this study, alterations in the binding affinity or intracellular localization of these proteins may also contribute to the changes in Tfam stability. Furthermore, other proteins or noncoding RNAs (micro-RNAs) may also play a role in explaining our data. Nonetheless, it remains possible that the increased expression of both of the measured destabilizing RBPs contributes to the reduction in Tfam transcript stability after 7 days of denervation. We have identified multiple putative sequence elements in the 3′-UTR of the rat Tfam gene (data not shown), which, on the basis of sequence specificity of the above-mentioned RBPs, may represent binding sites for these proteins. Future work will examine possible interactions between RBPs and these elements in the Tfam 3′-UTR.

In sum, it appears that there are factors, albeit unknown at this time, regulating the Tfam promoter during the earliest stages following denervation. These effects are counteracted by alterations in the stability of the Tfam transcript. Ultimately, import of Tfam into the mitochondrion appears to be a crucial point in the regulation of Tfam activity during the early stages of denervation. Reductions in Tfam import occurred in concert with the decline in mitochondrial content, and we previously showed that COX activity is positively correlated with the rate of mitochondrial protein import (48). Thus the decrease in mitochondrial content as a result of denervation-induced muscle disuse is a result of diminished synthesis pathways, in part mediated by Tfam, along with the substantial increases in mitochondrial-specific autophagy (i.e., mitophagy) observed with sustained denervation (39, 50). Future studies should strive to determine the upstream signals regulating the Tfam promoter during denervation and could seek to further elucidate the processes that contribute to the reduction in mitochondrial content within the first 72 h of denervation.

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DISCLOSURES

No conflicts of interest, financial or otherwise, are declared by the authors.
AUTHOR CONTRIBUTIONS

L.D.T. and D.A.H. developed the concept and designed the research; L.D.T. and M.J.C. performed the experiments; L.D.T., M.J.C., and D.A.H. analyzed the data; L.D.T. and D.A.H. interpreted the results of the experiments; L.D.T. prepared the figures; L.D.T. drafted the manuscript; L.D.T. and D.A.H. edited and revised the manuscript; L.D.T. and D.A.H. approved the final version of the manuscript.

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