Thyroid hormone receptors are down-regulated in skeletal muscle of patients with non-thyroidal illness syndrome secondary to non-septic shock

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Abstract

Aim: Non-thyroidal illness syndrome (NTIS) is related to changes in thyroid hormone (TH) physiology. Skeletal muscle (SM) plays a major role in metabolism, and TH regulates SM phenotype and metabolism. We aimed to characterize the SM of non-septic shock NTIS patients in terms of: i) expression of genes and proteins involved in TH metabolism and actions; and ii) NFKB’s pathway activation, a responsible factor for some of the phenotypic changes in NTIS. We also investigated whether the patient’s serum can induce in vitro the effects observed in vivo.

Methods: Serum samples and SM biopsies from 14 patients with non-septic shock NTIS and 11 controls. Gene and protein expression and NFKB1 activation were analyzed by quantitative PCR and immunoblotting. Human SM cell (HSkMC) cultures to investigate the effects of patient’s serum on TH action mediators.

Results: Patients with non-septic shock NTIS showed higher levels of pro-inflammatory cytokines than controls. Expression of TRβ (THRB), TRα1 (THRA), and retinoid X receptor γ (RXRG) was decreased in NTIS patients. RXRA gene expression was higher, but its protein was lower in NTIS than controls, suggesting the existence of a post-transcriptional mechanism that down-regulates protein levels. NFKB1 pathway activation was not different between NTIS and control patients. HSkMC incubated with patient’s serum increased TH receptor and RXRG gene expression after 48 h.

Conclusions: Patients with non-septic shock NTIS showed decreased expression of TH receptors and RXRs, which were not related to increased activation of the NFKB1 pathway. These findings could not be replicated in cultures of HSkMCs incubated in the patient’s serum.

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Introduction

Non-thyroidal illness syndrome (NTIS) forms a part of the neuroendocrine response to metabolic stress (1), and is characterized by a low 3,3′,5′-triiodothyronine (T3) and normal-high 3,3′,5′-triiodothyronine (reverse of T3, rT3) in serum and tissues, normal or low serum thyroxine (T4), and inappropriately normal or low serum TSH in relation to serum levels of T4 and T3 (2). Whether NTIS is a beneficial adaptive response to reduce energy consumption, or a form of secondary hypothyroidism that requires thyroid hormone (TH) treatment is controversial (3–6).

The inappropriately normal or low serum TH levels in NTIS patients are due to an impairment of hypothalamic–pituitary function (7, 8), a situation where TH replacement could be beneficial. However, the molecular changes observed in some peripheral tissues from patients with NTIS seem to be directed at decreasing TH action. In humans, T3 is mainly produced by extrathyroidal enzymatic deiodination of T4, mainly in the liver and skeletal muscle (SM) (9). Low T3 and elevated rT3 levels observed in NTIS patients are related to a decrease in liver type 1 iodothyronine deiodinase (DIO1) and SM type 2 iodothyronine deiodinase (DIO2) activities, and to an increase in type 3 iodothyronine deiodinase (DIO3) activity in the liver and SM (9–11). Patients with fatal NTIS have decreased T4 and T3 in most tissues (12, 13) caused in part by reduced tissue uptake, although TH bioavailability is...
not limited if appropriate replacement therapy is given (2). A decrease in mRNA expression of the TH receptors such as TH receptor α (THRA) and TH receptor β (THRβ) and their nuclear partner retinoid X receptor γ (RXRG) has been reported in SM and subcutaneous adipose tissue of patients with NTIS caused by septic shock (11). The functional consequences of decreased TH receptors and RXRG expression remain unknown, but a priori these findings suggest that TH replacement might be less effective in NTIS patients than in patients with hypothyroidism.

Many of the molecular mechanisms responsible for the above-described changes remain to be characterized. Increased levels of pro-inflammatory cytokines, endogenous glucocorticoids, and glucagon, typically seen in critically ill patients, together with the administration of glucocorticoids and dopaminergic drugs, could directly suppress TRH secretion, the pituitary response to TRH, and TSH secretion (7, 8, 14). Patients with NTIS have altered TSH glycosylation, which is associated with reduced biological activity (15), and lethal NTIS is associated with major morphological changes in the thyroid gland, including loss of colloid and reductions in follicular size and thyroid weight (16). Cytokines affect thyroid cell function in several ways (14, 17), including a decrease in basal and TSH-stimulated iodide uptake due to interleukin 1 (IL1) and tumor necrosis factor-α (TNF-α), inhibition of thyroglobulin synthesis by IL1, TNF-α (TNF), and interferon-γ (IFN-γ), a decrease in thyrperoxidase expression by IL1, IL6, and IFN-α (IFNA1), and a decrease in T3 secretion by IL1, TNF-α and IFN-γ (IFNG).

Nuclear factor of kappa light chain enhancer of activated B cells (NFκB) is a family of transcription factors that plays a pivotal role in immune and inflammatory responses. Activated NFκB1 is a potential molecular factor at the root of NTIS in patients with septic shock and increased serum cytokines level (18); in vitro studies using HepG2 cells have shown that NFκB1 activation attenuates the induction of DIO1 by T3 (18), and that the decrease in DIO1 mRNA expression induced by IL1β (IL1B) is mediated by the simultaneous activation of NFκB1 and AP-1 pathways (19).

SM is a major contributor to resting metabolic rate and plays a crucial role in protein metabolism (20). TH controls expression of more than 50% of SM genes (21) and, together with neuronal activity and physical exercise, regulates the cytoarchitecture and metabolic characteristics of SM. TH stimulates the development of exercise, regulates the cytoarchitecture and metabolic and, together with neuronal activity and physical controls expression of more than 50% of SM genes (21) and plays a crucial role in protein metabolism (20). TH reticulum (SR), a source of heat generation; expression a priori but RXRG TH receptors and shock(11). The functional consequences of decreased adipose tissue of patients with NTIS caused by septic adscription. Increased levels of pro-inflammatory cytokines, endogenous glucocorticoids, and glucagon, typically seen in critically ill patients, together with the administration of glucocorticoids and dopaminergic drugs, could directly suppress TRH secretion, the pituitary response to TRH, and TSH secretion (7, 8, 14). Patients with NTIS have altered TSH glycosylation, which is associated with reduced biological activity (15), and lethal NTIS is associated with major morphological changes in the thyroid gland, including loss of colloid and reductions in follicular size and thyroid weight (16). Cytokines affect thyroid cell function in several ways (14, 17), including a decrease in basal and TSH-stimulated iodide uptake due to interleukin 1 (IL1) and tumor necrosis factor-α (TNF-α), inhibition of thyroglobulin synthesis by IL1, TNF-α (TNF), and interferon-γ (IFN-γ), a decrease in thyrperoxidase expression by IL1, IL6, and IFN-α (IFNA1), and a decrease in T3 secretion by IL1, TNF-α and IFN-γ (IFNG).

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SM is a major contributor to resting metabolic rate and plays a crucial role in protein metabolism (20). TH controls expression of more than 50% of SM genes (21) and, together with neuronal activity and physical exercise, regulates the cytoarchitecture and metabolic characteristics of SM. TH stimulates the development of slow muscle fiber characteristics in SM: T3 induces a shift from myosin heavy chain 1 (MYH1), mainly expressed in slow oxidative muscle fibers, to MYH4, typically expressed in the fast glycolytic muscle fibers (22). T3 also regulates Ca^2+ cycling by the sarcoplasmic reticulum (SR), a source of heat generation: expression of SERCA1 (ATP2A1), a SR Ca^2+-ATPase predominantly expressed in fast muscle fibers, is increased by T3 in slow muscle fibers simultaneously with the shift from MYH1 to MYH4 in these fibers (23). T3, through genomic and non-genomic actions, increases lipid oxidation and glycolysis in SM (24), although overall ATP production remains constant since TH increases energy uncoupling and expenditure. Finally, TH increases protein breakdown and the efflux of branched chain amino acids from the muscle (25).

Injurious stimuli increase adipose tissue lipolysis that increases availability of fatty acids to different tissues as a source of energy (26). Peroxisome proliferator-activated receptor γ (PPARγ) plays a central role in lipid and glucose metabolism and is important for maintaining insulin sensitivity. PPARγ expression is positively regulated by T3 (27), and it forms heterodimers with RXRs, nuclear receptor co-repressor 1 (NCOR1), and NCOR2 (NCOR2 or SMRT) (28), competing with TH receptors for these proteins. In mice, lipopolysaccharides (LPS) cause a decrease in expression levels of TH receptors and PPARγ in several tissues (26), and several members of the multiprotein complex that regulate the transcriptional activity of PPARγ are affected during NTIS (11). However, the changes and involvement of PPARγ in human NTIS remain unknown.

To gain further insights into human NTIS pathophysiology, we investigated some of the molecular changes related to TH metabolism and actions in SM samples from a group of patients with NTIS admitted into an intensive care unit (ICU) for non-septic shock. Specifically, we quantified the following: i) mRNA expression of TH transporter monocarboxylate transporter 8 (MCT8 or SLC16A2), DIO2, THRA, THRβ1, RXRA, RXRB, RXRG, PPARγ, NCOR1, NCOR2, and nuclear receptor co-activator 1 (NCOA1), glucocorticoid receptor α, nuclear receptor subfamily 3, group C, member 1 (NR3C1 or GCR), and the TH-responsive genes, solute carrier family 2, member 4 (GLUT4 or SLC2A4), uncoupling protein 3 (UCP3), lipoprotein lipase (LPL), the MYH genes MYH1 SM adult (MYH1) and MYH4 SM (MYH4 or MyHC-IIb), and the SR calcium ATPases ATPase Ca++ transporting, cardiac muscle, fast twitch 1 (ATP2A1 or SERCA1) and ATPase Ca++ transporting, cardiac muscle, slow twitch 2 (ATP2A2 or SERCA2); ii) protein expression levels of THRA, THRβ1, RXRG, RXRB, and PPARγ; and iii) mRNA expression of nuclear factor NF-kappa-B p50 subunit (nuclear factor of kappa light polypeptide gene enhancer in B cells 1 or NFκB1) and p65 (v-rel reticuloendotheliosis viral oncogene homolog A (avian) or RELA), together with activation of the NFκB1 pathway. Finally, we sought to determine whether the changes observed in mRNA expression of MCT8, THRA, THRβ1, and RXRG in SM in vivo could be reproduced in vitro by incubating cells from a human SM cell line (HSkMC) in serum from patients with NTIS.

Our results showed that patients with non-septic shock NTIS have a decreased expression of TH receptors in the SM, which is not mediated by an activation of the NFκB1 pathway.

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Materials and methods

Subjects

The study was conducted on two groups of patients with no previous history of thyroid disease. The control group comprised 11 patients (7 males and 4 females), median age 62 years (range 37–77), selected from among those referred to our hospital for knee or hip replacement. The non-septic NTIS group comprised 14 ICU patients (11 males and 3 females), median age 57 years (range 45–89), hospitalized for multiple traumatic injuries (n = 4), intracranial hemorrhage (n = 8), cardiac arrest during hemodialysis (n = 1), and food asphyxia (n = 1). NTIS patients were transferred to ICU for ventilatory and circulatory support. Low-medium dosage of noradrenaline was administered to six patients. Sedation and analgesia were maintained by continuous i.v. infusion of propofol and morphine, and nutrients were given by continuous total parenteral nutrition. Eight patients (57.14%) recovered after a median stay in ICU of 5.37 days (range 1–11 days), and six patients (42.86) died in ICU.

SM biopsies were obtained from the vastus lateralis muscle as previously described (11). The biopsies were obtained during surgery in control patients and in the first 48 h after ICU admission in NTIS patients.

In all cases, informed consent was obtained from the control patients or the closest family member of the ICU patients. The study protocol was approved by the Ethical Review Board of the Medical School of the University of Santiago de Compostela.

Serum analysis

Blood samples were obtained immediately before surgery in the control group and before the muscle biopsy in the non-septic NTIS group. Chemiluminescence was used to measure serum TSH (normal 0.41–4.94 mU/l), free T4 (FT4, normal 0.85–1.60 ng/dl, 10.94–21.75 pmol/l), free T3 (FT3, normal 2.53–4.29 pg/ml, 0.039–0.066 pmol/l) (ADVIA Centaur, Bayer Diagnostics), total cortisol (g/dl), TNF-α (ng/l), IL2 receptor (IL2R, U/ml), IL6 (ng/l), and IL8 (ng/l) (Immulite 2000, DPC, Gwynedd, UK). rT3 (normal 0.15–0.35 ng/ml, 0.23–0.54 nmol/l) was measured by RIA (Biodex Hycel, Massy, France). Thyroperoxidase antibodies (TPOAb) and thyroglobulin antibodies (TgAb) were measured by an ELISA (Orgentec Diagnostika, Mainz, Germany).

HSkMCs culture for in vitro studies

Primary HSkMCs (ScienCell Research Laboratories, San Diego, CA, USA) were incubated in 12-well plates using media recommended by the manufacturer. At 80–90% of confluence, growth medium was changed for a basal medium of DMEM plus 20% of a pool of human serum from control subjects or non-septic NTIS patients supplemented with gentamicin (50 μg/ml). Incubation was stopped at 0, 6, 12, 24, 48, and 72 h, and cells were harvested for RNA extraction and quantification of gene expression as described below.

Total RNA isolation and real-time quantitative PCR

Total RNA from SM biopsies and HSkMC cell cultures was extracted from TRIzol reagent (Invitrogen) according to the manufacturer’s instructions. cDNA synthesis was generated from 1 μg of total RNA using 5 μM random hexamers, 2 mM deoxynucleotides (Ecogen, Madrid, Spain), and M-MLV reverse transcriptase (Invitrogen).

Gene expression changes were quantified by quantitative PCR (QPCR). mRNA expression of MCT8, THRA, THRBS1, and RXRG was evaluated in both SM biopsies and HSkMC cells; mRNA expression of DIO2, RXRA, RXRB, PPARG, SRC1, NCOA1, SMART, NCOA1, GLUT4, UCP3, PLP, NRC1, MYH1, MYH4, SERCA1, SERCA2, NFKB1, and RELA was measured in SM biopsies. QPCRs were performed in a LightCycler 2.0 (Roche) using specific probes and oligonucleotide primers designed by Universal ProbeLibrary (Roche) as previously described (11). Gene expression was normalized to RNA polymerase II following the 2−ΔΔCt method (29).

Immunoblotting

Owing to the limited amount of SM tissue available from biopsies and the high protein concentration required for western blotting (25–75 μg/lane), total protein extracts were used instead of cytoplast and nucleus protein. Total protein extraction was obtained after sonication of SM biopsies in 150 μl RIPA buffer, pH 7.4 (50 mM Tris–HCl, pH 8, 150 mM NaCl, 1% NP-40, 0.5% sodium deoxycholate, and 0.1% SDS), containing protein inhibitors (phenylmethylsulfonyl fluoride (PMSF), and sodium orthovanadate (Na3VO4); each at 1 μM final concentration). The lysate was centrifuged for 30 min at maximum speed (16 000 g), and the supernatant was collected. Protein was quantified using the Bradford method, and equal amounts of protein were run on an SDS-PAGE (10% polyacrylamide gel). After electrophoresis, the proteins were transferred to a nitrocellulose membrane and blocked for at least 1 h with 5% dried milk powder in TBS. The membrane was then incubated overnight with the first antibodies (dilution 1:1000 in blocking solution) against THRBS1 (Acris Antibodies, AntibodyBcn SL, Barcelona, Spain, SM5022), THRA (Santa Cruz, Heidelberg, Germany, sc-772), PPARG (Santa Cruz, sc-772), RXRG (Santa Cruz, sc-555), RXRA (Santa Cruz, sc-553), and β-tubulin (Sigma, T-5168). After three washes of 10 min each with 0.2% TBS Tween 20 (TBS-T), the membrane was incubated with the appropriate HRP-conjugated secondary antibodies and subsequently with the appropriate HRP-conjugated reagents. After washing, the bands were visualized using an ECL kit (Roche).
secondary antibody (Sigma). Proteins were detected using ECL (Amersham). Quantification was performed using AlphaEaseFC software and normalized with β-tubulin.

NFκB1 pathway activation

The status of activation of the NFκB1 pathway was determined by analysis of cytoplasmic IkBα (NFκB1A) phosphorylation. After homogenization in PBS, samples were centrifuged for 5 min at 500 g at 4 °C and resuspended in a sucrase buffer (0.32 M sucrose, 10 mM Tris–HCl, pH 8.0, 3 mM CaCl2, 2 mM MgOAc, 0.1 mM EDTA, 0.5% NP-40, 1 mM dithiothreitol, and 0.5 mM PMSF); cytoplasmic fractions were recovered after centrifugation of the samples for 5 min at 500 g at 4°C to precipitate the nuclei. Cytoplasmic samples (40 µg/lane) were run and transferred as described above, blocked for 1 h in TBS-T and 3% BSA, and incubated overnight at 4°C with the primary antibody (anti-IkBα Ab (pS32/pS36); Biomol International, Hamburg, Germany, Grupo Taper SA, Madrid, Spain, SA-412) diluted to 1:1000 in blocking solution; anti-GAPDH (AbCam, Cambridge, MA, USA ref Ab9485) was used as a loading control. Membranes washing incubation with HPR-conjugated secondary antibody and quantification of proteins were performed as described above. Quantification was normalized with GAPDH.

To demonstrate the specificity of the phosphorylation site-specific antibody, a peptide competition experiment was performed using an IkBα (pS32/pS36) control peptide pair (Biomol International, SP-412).

Statistical analysis

Data were analyzed using SPSS 12.0 for Windows (SPSS, Chicago, IL, USA). Results are expressed as mean ± s.d., median, and range. The groups were compared by Student’s t-test or the Mann–Whitney non-parametric test, as appropriate.

Results

Age and body mass index (BMI) were not significantly different between non-septic NTIS and control patients (Table 1). Non-septic NTIS patients had significantly lower serum TSH and FT3, and higher rT3 levels than controls, while no differences were found in serum FT4 (Table 1). TNF-α, IL6, IL8, and IL2R were all significantly higher in non-septic NTIS patients than in controls (Table 1). Although non-septic NTIS patients presented higher serum cortisol levels than controls, no statistically significant differences were observed. TPOAb and TgAb were negative in all patients.

mRNA expression in SM biopsies

In controls, SERCA and MYH1 genes showed the highest expression levels, and MCT8 and MYH4 genes showed the lowest expression levels (Fig. 1). Glucocorticoid receptor α, NR 3C1, RXRA, GLUT4, UCP3, and LPL genes were all highly expressed in SM (Fig. 1). Non-septic NTIS patients had lower expression levels of THRB1, THRA, RXRG, and DIO2, but higher

Table 1 Anthropometric and biochemical data for the control and non-septic shock non-thyroidal illness syndrome (NTIS) patients.

<table>
<thead>
<tr>
<th></th>
<th>Control</th>
<th>NTIS</th>
<th>P</th>
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<tbody>
<tr>
<td>Age (years)</td>
<td>61.33±6.26</td>
<td>62.29±4.04</td>
<td>NS</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>30.04±1.24</td>
<td>27.57±0.90</td>
<td>NS</td>
</tr>
<tr>
<td>TSH (mU/l)</td>
<td>23.14 (25.51–40.70)</td>
<td>26.30 (24.08–35.62)</td>
<td>P&lt;0.01</td>
</tr>
<tr>
<td>FT4 (ng/dl)</td>
<td>1.19±0.06</td>
<td>1.22±0.11</td>
<td>NS</td>
</tr>
<tr>
<td>FT3 (pg/ml)</td>
<td>1.19 (0.92–1.61)</td>
<td>1.26 (0.64–1.90)</td>
<td>P&lt;0.001</td>
</tr>
<tr>
<td>rT3 (ng/ml)</td>
<td>2.74 (2.18–3.48)</td>
<td>1.84 (0.92–2.35)</td>
<td>P&lt;0.01</td>
</tr>
<tr>
<td>Cortisol (µg/dl)</td>
<td>15.50±2.27</td>
<td>25.93±6.18</td>
<td>NS</td>
</tr>
<tr>
<td>TNF-α (ng/l)</td>
<td>4.1±0.19</td>
<td>2.71±0.94</td>
<td>P&lt;0.001</td>
</tr>
<tr>
<td>IL6 (ng/l)</td>
<td>11.56±1.31</td>
<td>143.2±106.7</td>
<td>P&lt;0.001</td>
</tr>
<tr>
<td>IL2R (U/ml)</td>
<td>440±44</td>
<td>2032±795</td>
<td>P&lt;0.001</td>
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Data are shown as mean±s.d. (upper), median, and range (lower).
expression levels of RXRA, RXRB, UCP3, and GLUT4 than control patients (Fig. 1). No differences between NTIS and control patients were observed for MCT8, NCOR1, SMART, NCOA1, LPL, PPARG, NR3C1, MYH1, MYH4, SERCA1, or SERCA2 (Fig. 1).

**Protein expression in SM biopsies**

To evaluate whether changes in mRNA expression were accompanied by changes in protein levels, we analyzed the protein expression of THRA (55 kDa), THRB1 (52–55 kDa), RXRG (51 kDa), RXRA (54 kDa), and PPARB (67 kDa) normalized with β-tubulin (50 kDa). Immunoblotting of RXRs showed the expected 51 kDa (RXRG) and 54 kDa (RXRA) weights (Fig. 2). A band that did not correspond to the size predicted was also observed, which could represent an alternative and unknown RXR isoform, reflecting the molecular complexity of RXRs. The THRB1 antibody turned out to be relatively unspecific, and only the band expected from the control test (nuclear protein extract from placenta) is shown (Fig. 2). THRB1, RXRG, and RXRA expression levels were significantly lower in non-septic NTIS patients than in control patients (Fig. 2); although THRA expression was lower in non-septic NTIS patients than in controls, statistical significance was not reached. No differences were observed in PPARG expression between the two groups (Fig. 2).

**Expression of p50 and p65 subunits and NFKB1 activation status in SM**

mRNA expression of NFKB1 (p50) and RELA (p65) was significantly elevated in non-septic NTIS patients versus controls (Fig. 3A).

IkBα immunoblotting showed two bands, a 40 kDa product corresponding to phosphorylated IkBα and a 36 kDa product that corresponds to non-phosphorylated IkBα (Fig. 3B). No statistically significant differences were observed in IkBα phosphorylation between non-septic NTIS and control patients.

**Effects of patient’s serum on mRNA expression of MCT8, THRB1, THRA, and RXRG in HSkMC cultures**

HSkMC cultured in serum from control patients showed a significant increase in mRNA expression of THRA, THRB1, and RXRG at 48 and 72 h. By contrast, MCT8 expression increased at 6 and 12 h, but at 24 h, it had returned to basal expression levels with no further changes observed at 48 or 72 h (Fig. 4). HSkMC cultured in serum from NTIS patients showed a similar response, although the expression of THRB1 was higher at 48 and 72 h with respect to controls (Fig. 4).

**Discussion**

NTIS is caused by an impairment of hypothalamic–pituitary function and of the physiological mechanisms producing T3 in peripheral tissues in response to moderate–severe illness and starvation. Depending on the severity of the noxious agent, extent of damage, and time taken to recover, several molecular changes affecting the transport, tissue uptake, metabolism, and action of THs can be observed (30). Although the molecular mechanisms responsible for NTIS remain speculative, the changes are tissue-specific (11).

SM has a crucial role in protein metabolism and contributes to the resting metabolic rate of the organism. Since TH regulates a large number of SM genes (21), we aimed to investigate some of the molecular changes in TH metabolism and action occurring in the SM of patients with NTIS. Previously, we have shown that SM from patients with NTIS...
degradation of RXRA. Under catabolic conditions, transcriptional abnormality in the synthesis or protein levels, suggesting the existence of a post-

dependence on its dimerization with different RXR isotypes, in addition, proteasomal degradation of its protein product could affect PPAR activity as shown in obese human adipose tissue (35); PPAR action depends on its dimerization with different RXR isotypes, and a decrease in RXRA has been shown to increase transcriptional activity of PPAR (35). Finally, a decrease in RXRs could protect SM cells from apoptosis during the stressful conditions of NTIS (37).

Unexpectedly, no changes were observed in mRNA expression levels of the TH-responsive genes MYH1, MYH4, SERCA1, and SERCA, and the expression of UCP3 and GLUT4, two genes up-regulated by TH, was higher in non-septic shock NTIS patients than in control patients. T3 content of SM biopsies was not measured due to the small amount of tissue available, although it is reasonable to assume that it was low in NTIS SM, since not only serum levels of T3 but also mRNA expression of secondary to septic shock caused by Gram-negative bacteria shows a decrease in the TH receptors, THRA and THRβ1, as well as in RXRG (11). LPS plays a central role in the pathophysiology of septic shock caused by Gram-negative bacteria. LPS binds to Toll-like receptor 4 (TLR4), activating the NFKB1 pathway that in turn increases transcription of a range of genes associated with inflammation and immunity, thus causing a strong inflammatory response. TLR4 is present in SM (31), and LPS binding to TLR4 could therefore underlie the changes observed in the SM of patients with septic shock-associated NTIS; indeed, mice deficient in TLR4 do not develop NTIS in response to LPS, and bacterial-related NTIS requires the activation of TLR–MyD88 pathway which leads to the production of inflammatory cytokines (32). However, the patients with non-septic shock NTIS also had decreased levels of TH receptors and RXRG mRNA, and protein expression in SM, suggesting that this pattern constitutes a common response of SM during NTIS.

TH promotes proteolysis and a shift from the more energetically efficient slow oxidative muscle fibers to fast glycolytic muscle fibers, increasing energy uncoupling and thus the expenditure of energy as heat. The decreases in TH receptor levels and RXRG mRNA could therefore comprise a mechanism to prevent energy expenditure as well as to protect proteins from being broken down (25) under situations of low SM activity. Interestingly, non-septic NTIS patients showed an increase in RXRA mRNA expression but a decrease in protein levels, suggesting the existence of a post-transcriptional abnormality in the synthesis or degradation of RXRA. Under catabolic conditions, there is an ubiquitin–proteasome-dependent protein degradation (33), and RXRA suffers post-translational regulation by ubiquitination resulting in its rapid degradation (34, 35). This mechanism could explain the decrease in RXRA protein levels in NTIS patients. TH receptor binding to MYH is increased by RXRA (36), so a decrease in both transcription factors could constitute a mechanism to prevent TH altering the SM phenotype. Moreover, a decrease in TH receptors, RXRA, and RXRG, would reduce uptake and oxidation of fatty acids by SM, an effect that could be counteracted, however, by an increase in PPAR transcriptional activity. The RXRA gene is highly expressed in SM suggesting an important regulatory role. In addition, proteasomal degradation of its protein product could affect PPAR activity as shown in obese human adipose tissue (35); PPAR action depends on its dimerization with different RXR isotypes, and a decrease in RXRA has been shown to increase transcriptional activity of PPAR (35). Finally, a decrease in RXRs could protect SM cells from apoptosis during the stressful conditions of NTIS (37).

Figure 3 (A) mRNA expression of NFKB1 (p50) and RELA (p65), two major components of the NFKB1 pathway, was increased in SM biopsies from NTIS patients. (B) No differences in SM IκBα phosphorylation levels were observed between control and NTIS patients. *P<0.05, **P<0.01.

Figure 4 Cells from a primary human skeletal muscle cell line, HSkMC, were incubated for 72 h in serum from control or NTIS patients to evaluate changes in THRA, THRβ1, RXRG, and MCT8 gene expression. THRA, THRβ1, and RXRG expression did not change from 0 to 24 h, but had increased significantly at 48 and 72 h. No differences were observed between cells incubated in control or NTIS serum with respect to THRA and RXRG expression, but at 48 and 72 h, THRβ1 expression was significantly higher in cells incubated in serum from NTIS patients. By contrast, MCT8 expression had not increased at 48 and 72 h in either groups. *P<0.05 NTIS versus controls.
DIO2 was lower in non-septic shock NTIS SM than in control SM. In mice under TH deprivation, the response of TH positively regulated genes is variable, and some of these genes do not show basal repression (38). This has also been observed in NTIS patients in our study, although the mechanisms responsible for these changes are unknown. It is possible that the non-repressed genes recruit co-repressors weakly or not at all in the absence of TH, or that the repressive effect of the unliganded TH receptors is overcome by the action of other transcription factors. UCP3 gene transcription is up-regulated by TH through both THRA and THRB1 receptors; UCP3 expression is also increased under circumstances where fatty acids are elevated likely during starvation (39), which is a cause of NTIS. Although not measured in the present study, the serum levels of fatty acids were probably elevated in ICU patients because they frequently receive i.v. heparin, and lipolysis is increased under severe stressful situations. TH increases GLUT4 expression in SM, causing an increase in basal and insulin-stimulated glucose transport (40, 41). GLUT4 mRNA expression is higher in slow oxidative muscle fibers than in fast glycolytic muscle fibers (42), due in part to a muscle-specific GLUT4 promoter enhancer that contributes to these differences (43). This enhancer contains three co-operative elements, a myocyte enhancer factor 2 (MEF2)-binding site, a low-affinity binding site for TH receptors, and a MyoD-binding site next to the MEF2 site (43). Interestingly, under normal conditions (non-damaged muscle), the thyroid response element-binding site blocks the promoter activity. The greater activity of the muscle-specific GLUT4 enhancer in oxidative muscles than in glycolytic muscles is a consequence of a greater activity of the MEF2-binding site (43). A decrease in TH and TH receptor expression levels could increase the activity of MEF2 and the ratio of oxidative to fast muscle fibers, explaining in part why NTIS patients showed higher GLUT4 expression levels than controls. A higher expression of SM MEF2 isoforms that operate in the enhancer could also contribute to the higher level of GLUT4 expression in NTIS patients. Overall, these unexpected changes seem to be the result of compensatory mechanisms that remain to be elucidated.

The NTIS patients have significantly increased serum levels of the pro-inflammatory cytokines IL6, IL8, IL2R, and TNF, which have been shown to decrease expression levels of THRA, THRB1, and RXRA in liver cells (19, 44–46). Since pro-inflammatory cytokines activate NFKB1 pathway, we investigated whether NFKB1 was activated in SM from patients with non-septic shock NTIS. The NFKB1 family is composed of five members that include NFKB1 or p50 and RELA or p65 subunits that are responsible for many of the actions of NFKB1. NFKB1 members form heterodimers that are sequestered into the cytoplasm bound to nuclear factor of kappa light polypeptide gene enhancer in B-cell inhibitors or IkB proteins that inhibit dimer migration to the nucleus; p50–p65 dimers are retained in the cytoplasm by IkBz. NFKB1 is activated in response to a variety of stimuli that bind to the TLR4; the classical NFKB1 pathway is activated by cytokines and bacterial LPS through activation of inhibitory kB kinases (IKKs). IKKs phosphorylate IkBz at serines 32 and 36, causing the release of p50–p65 heterodimers that are free to migrate to the nucleus where they regulate gene transcription. NFKB1 (p50) and RELA (p65) mRNA expression levels were increased in non-septic shock NTIS SM, suggesting that the classical NFKB1 pathway might have been activated. Phosphorylation-based signal transduction is often transient, but an increased steady-state level of IkBz phosphorylation has been reported under several conditions that activate the NFKB1 pathway in lymphocytes from hyperthyroid rats (47), acute lymphoblastic leukemia cells (48), or melanoma cells (49).

No differences were observed in IkBz phosphorylation levels between non-septic shock NTIS and control patients, indicating that the SM of patients with NTIS did not have a more highly activated NFKB1 pathway. Thus, the changes observed in gene and protein expression between the two groups could not be attributed to changes in activation of the NFKB1 pathway.

HSkMCs incubated in serum from patients with NTIS did not show decreased mRNA expression of MCT8, THRB1, THRA, or RXRγ. Indeed, not only the expression of TH receptors but also the expression of RXRγ increased in cells incubated either in serum obtained from NTIS patients or in serum obtained from control patients; THRB1 expression was higher in cells incubated in NTIS serum than in control serum at 48 and 72 h. These unexpected results might be attributed to the fact that cells were incubated in 20% serum that has lower concentration of ILs than 100% serum. On the other hand, the fact that THRB1 expression increased in cells incubated in NTIS serum argues against the presence of inhibitory factors in serum in vivo being responsible for changes observed in patients. Patients with critical illness may have an over-activated sympathetic nervous system that can lead to adverse consequences (50); however, the likely role of a sympathetic nervous system response in the pathophysiology of NTIS remains unknown.

In conclusion, SM from patients with non-septic shock NTIS showed decreased gene and protein expression levels of TH receptors and RXRs. The decrease in TH receptors did not significantly affect the expression of genes important to SM physiology. No differences in IkBz phosphorylation were observed in the SM of NTIS and control patients, suggesting that activation of the classical NFKB1 pathway seems to be not responsible for the decreases found in TH receptor and RXR expression levels. Finally, TH receptor and RXRs expression in primary cultures of HSkMCs did not decrease when exposed to serum from NTIS patients.
suggested that the changes observed in vivo could be mediated by serum-independent factors or mechanisms.

Declaration of interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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Author contribution statement

J Lado-Abeal conceived the study, participated in its design and coordination, got the research funds, and wrote the manuscript. A Romero carried out the genetic and protein expression analyses and the cell culture studies. I Castro-Piedras carried out the NFKB1 studies. A Rodriguez-Perez and J Alvarez-Escudero participated in the study design, selected the patients, got the consents, and performed the biochemical analyses and the muscle biopsies.

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