Thyroid hormones induce browning of white fat

Noelia Martínez-Sánchez1,2, José M Moreno-Navarrete2,3, Cristina Contreras1,2, Eva Rial-Pensado1,2, Johan Ferno1,4, Rubén Nogueiras1,2, Carlos Diéguez1,2, José-Manuel Fernández-Real2,3 and Miguel López1,2

1Department of Physiology, CIMUS, University of Santiago de Compostela-Instituto de Investigación Sanitaria, Santiago de Compostela, Spain
2CIBER Fisiopatología de la Obesidad y Nutrición (CIBERobn), Santiago de Compostela, Spain
3Department of Diabetes, Endocrinology and Nutrition, Hospital de Girona ‘Dr Josep Trueta’, Institut D’investigació Biomèdica de Girona (IdIBGI) and University of Girona, Girona, Spain
4Department of Clinical Science, KG Jebsen Center for Diabetes Research, University of Bergen, Bergen, Norway

Abstract

The canonical view about the effect of thyroid hormones (THs) on thermogenesis assumes that the hypothalamus acts merely as a modulator of the sympathetic outflow on brown adipose tissue (BAT). Recent data have challenged that vision by demonstrating that THs act on the ventromedial nucleus of the hypothalamus (VMH) to inhibit AMP-activated protein kinase (AMPK), which regulates the thermogenic program in BAT, leading to increased thermogenesis and weight loss. Current data have shown that in addition to activation of brown fat, the browning of white adipose tissue (WAT) might also be an important thermogenic mechanism. However, the possible central effects of THs on the browning of white fat remain unclear. Here, we show that 3,3′,5,5′-tetraiodothyroxyne (T4)-induced hyperthyroidism promotes a marked browning of WAT. Of note, central or VMH-specific administration of 3,3′,5-triiodothyronine (T3) recapitulates that effect. The specific genetic activation of hypothalamic AMPK in the VMH reversed the central effect of T3 on browning. Finally, we also showed that the expression of browning genes in human WAT correlates with serum T4. Overall, these data indicate that THs induce browning of WAT and that this mechanism is mediated via the central effects of THs on energy balance.

Introduction

Thyroid hormones (THs; 3,3′,5,5′-tetraiodothyroxyne or T4 and 3,3′,5-triiodothyronine or T3) exert important biological actions, not only modulating the development and growth but also regulating metabolism and energy balance (Brent 2012, Warner & Mittag 2012, Lopez et al. 2013). Impaired function of the thyroid gland, by either hyperthyroidism or hypothyroidism, leads to alterations in metabolism and energy homeostasis. Hyperthyroidism is associated with an increase in the metabolic rate and the patients suffering from this condition undergo body weight loss, despite increased food intake; quite the opposite, hypothyroid patients show lowered metabolic rate and reduced food intake (Brenta et al. 2007, Kaptein et al. 2009, Pearce 2012).

THs are key regulators of thermogenesis, which represents a major component of the energy expenditure in homeothermic (‘warm-blooded’) animals (Cannon & Nedergaard 2004, Silva 2006). In mammals, including humans, thermogenesis occurs mainly in the brown adipose tissue (BAT) (Cannon & Nedergaard 2004,
Silva 2006, von Ballmoos et al. 2009). THs act on brown adipocyte thermogenesis by increasing the stimulatory action of norepinephrine (NE), as well as enhancing the cAMP-mediated acute rise in ucp1 gene expression (Bianco et al. 1988, Silva 2006, Ribeiro et al. 2010). The existence of central effects of THs in the regulation of BAT thermogenesis was proposed long time ago (Nedergaard et al. 1997). Recent evidence from our group has also shown a homeostatic link between the central effects of THs on hypothalamic AMP-activated protein kinase (AMPK), sympathetic tone and UCP1 expression in BAT (Lopez et al. 2010, Alvarez-Crespo et al. 2016).

Over the last years, accumulating evidence has demonstrated that activation of beige/brite (‘brown in white’) adipocytes in the white adipose tissue (WAT), a process known as browning (Fisher et al. 2012, Cohen et al. 2014, Nedergaard & Cannon 2014, Contreras et al. 2016b), is responsible for a significant increase in total energy expenditure (Shabalina et al. 2013). Thus, stimulation of browning has therapeutic potential to promote body fat reduction (Yoneshiro et al. 2013, Beiroa et al. 2014). Several mechanisms have been proposed for WAT browning (Villarroya & Vidal-Puig 2013, Nedergaard & Cannon 2014), including prolonged cold exposure (Loncar et al. 1986), adrenergic activation (Cousin et al. 1992, Ghorbani et al. 1997, Cao et al. 2011) and also thyroid hormone receptor (TR) agonism (Lin et al. 2015, Alvarez-Crespo et al. 2016). However, the role of central THs in the control of WAT browning remains unclear.

The aim of this study was to investigate the role of central THs on the browning of WAT and the mechanisms behind this action. Our data show that peripherally induced hyperthyroidism promoted browning of white fat and that this effect is recapitulated by central and specific administration of \(T_3\) in the ventromedial nucleus of hypothalamus (VMH), via a mechanism dependent of AMPK. Notably, we also demonstrate that the expression of browning markers in WAT correlates with serum \(T_4\) levels in humans. Thus, in addition to the well-known effects of central THs on BAT (Lopez et al. 2010, Alvarez-Crespo et al. 2016), our data indicate an additional mechanism by which central THs influence energy expenditure, namely browning of WAT.

Material and methods

Animals

Male Sprague–Dawley rats (200–250g; Animalario General USC, Santiago de Compostela, Spain) were housed on a 12-h light (08:00–20:00), 12-h darkness cycle, in a temperature and humidity controlled room and maintained with chow (STD, SAFE A04: 3.1% fat, 59.9% carbohydrates, 16.1% proteins, 2.791 kcal/g; Scientific Animal Food & Engineering; Nantes, France) and water ad libitum. For all the procedures, the animals were individually caged and used for experimentation 7 days later. During all experimental approaches, animals and their respective food intake and body weight were monitored every day. The experiments were performed in agreement with the International Law on Animal Experimentation and were approved by the USC Ethical Committee (Project ID 15010/14/006).

Patients

A group of 163 (80 visceral, vWAT and 83 subcutaneous, sWAT) white adipose tissues from participants were analyzed (Table 1). These participants were recruited at the Endocrinology Service of the Hospital of Girona ‘Dr Josep Trueta’. All subjects were of Caucasian origin and reported that their body weight had been stable for at least three months before the study. Subjects were studied in their post-absorptive state. They had no systemic disease other than obesity and all were free of any infections in the previous month before the study. Liver diseases (specifically tumoral disease and HCV infection) and thyroid dysfunction were exclusion criteria. All subjects gave written informed consent, validated and approved by the Ethics committee of the Hospital of Girona ‘Dr Josep Trueta’, after the purpose of the study was explained to them.

Induction of hyperthyroidism

Hyperthyroidism in rats was induced by chronic subcutaneous (SC) administration of \(1\)-thyroxine.
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**Intracerebroventricular treatments**

Intracerebroventricular (ICV) cannulas were stereotaxically implanted under ketamine/xylazine anesthesia, as previously described (Lopez et al. 2008, 2010, Whittle et al. 2012, Contreras et al. 2014, Martinez de Morentin et al. 2014, Alvarez-Crespo et al. 2016, Martins et al. 2016), using the following coordinates: 1.6 mm lateral to bregma, 0.6 mm posterior, 4.5 mm deep from the skull. Rats received a single ICV daily administration of T₄ (4 ng/day, during 5 days) dissolved in 5 µL of saline.

**Stereotaxic microinjection of T₄ and viral vectors**

Rats were placed in a stereotaxic frame (David Kopf Instruments; Tujunga, CA, USA) under ketamine/xylazine anesthesia. Nuclei-specific injections were delivered via a permanent 28-gauge stainless steel cannula (Plastics One, Roanoke, VA, USA) inserted bilaterally either in the VMH or the arcuate nucleus of the hypothalamus (ARC), following stereotaxic coordinates: (a) for the VMH: −2.8 mm posterior to the bregma, ±0.6 mm lateral to bregma and 10.1 mm deep from the skull; (b) for the ARC: −2.8 mm posterior to the bregma, ±0.3 mm lateral to bregma and 10.2 mm deep from the skull. A catheter tube was connected from each infusion cannula to an osmotic minipump flow moderator (Model 1007D; Alzet; Hamilton, Reno, NV, USA) vectors (Lopez et al. 2010, Alvarez-Crespo et al. 2016, Martins et al. 2016), inserted bilaterally under ketamine/xylazine anesthesia, as previously described (Lopez et al. 2008, 2010, Alvarez-Crespo et al. 2016, Martins et al. 2016). Adenoviral GFP or constitutive active AMPKα isoforms (AMPKα-CA; Viraquest; North Liberty, IA, USA) vectors (Woods et al. 2000, Minokoshi et al. 2004, Lopez et al. 2008, 2010) were delivered in the VMH of rats using a 25-gauge needle (Hamilton; Reno, NV, USA) and the stereotaxic coordinates: −2.4 mm and −3.2 mm posterior to the bregma, ±0.6 mm lateral to bregma and 10.1 mm deep at a rate of 200 nL/min for 5 min for rat (1 µL/injection site) as previously reported (Lopez et al. 2008, 2010, Martinez de Morentin et al. 2012, 2014, Whittle et al. 2012, Beiroa et al. 2014, Contreras et al. 2014, Martins et al. 2016). Animals were treated for 6 days.

**Blood biochemistry**

For the rat samples, plasma levels of T₃ and T₄ were measured using rat ELISA kits (Crystal Chem Inc; Downers Grove, IL, USA) (Lopez et al. 2010, Gonzalez et al. 2012, Varela et al. 2012). For the human samples, serum glucose concentrations were measured in duplicate by the glucose oxidase method using a Beckman Glucose Analyser II (Beckman Instruments; Brea, CA, USA). Roche Hitachi Cobas c711 instrument (Roche) was used to perform HDL cholesterol and total serum triglycerides determinations. HDL cholesterol was quantified by a homogeneous enzymatic colorimetric assay through the cholesterol esterase/cholesterol oxidase/peroxidase reaction (Cobas HDLC3; Roche). Serum fasting triglycerides were measured by an enzymatic, colorimetric method with glycerol phosphate oxidase and peroxidase (Cobas TRIGL; Roche). LDL cholesterol was calculated using the Friedewald formula. Serum free T₄ was measured by electrochemiluminescence (Roche Diagnostics) with intra- and inter-assay coefficients of variation less than 5%. Methods have been previously reported (Ortega et al. 2015, Gavalda-Navarro et al. 2016).

**Sample processing**

Rats were killed by cervical dislocation. From each animal, gonadal WAT (gWAT), subcutaneous inguinal WAT (sWAT) or both (only for the euthyroid and hyperthyroid animals) were harvested and immediately frozen in dry ice. Samples were stored at −80°C until further processing. Human adipose tissue samples were obtained from sWAT and vWAT depots during elective surgical procedures (cholecystectomy, surgery of abdominal hernia and gastric bypass surgery) (Ortega et al. 2015, Gavalda-Navarro et al. 2016). Samples of adipose tissue were immediately transported to the laboratory (5–10 min). Tissue handling was carried out under strictly aseptic conditions. Adipose tissue samples were washed in PBS, cut off with forceps and scalpel into small pieces (100 mg), and immediately flash-frozen in liquid nitrogen before storage at −80°C.

**Real-time PCR**

We performed real-time PCR (TaqMan; Applied Biosystems) as previously described (Lopez et al. 2010, Martinez de Morentin et al. 2012, 2014, Whittle et al. 2012, Contreras et al. 2014, Alvarez-Crespo et al. 2016, Martins et al. 2016), using specific sets of primers and probes for rat (Supplementary Table 1, see section on
supplementary data given at the end of this article). Values were expressed relative to hypoxanthine–guanine phosphoribosyltransferase (HPRT) levels. For the analysis of the human WAT samples, we used commercially available and pre-validated TaqMan primer/probe sets (Applied Biosystems) as follows: endogenous control peptidylprolyl isomerase A (cyclophilin A) (PPIA, 4333763), PR domain containing 16 (PRDM16, Hs00223161_m1), uncoupling protein 1 (UCP1, Hs0022453_m1) and cell death-inducing DFFA-like effector a (CIDEA, Hs00154455_m1). Gene expression values were expressed relative to PPIA levels.

Histology and immunohistochemistry

Adipose tissue depots were fixed in 10% buffered formaldehyde. For the hematoxylin–eosin staining, the WAT sections were first stained with hematoxylin for 5 min, washed and stained again with eosin for 1 min. The detection of UCP1 in WAT was performed using anti-UCP1 (1:500; ab10983; Abcam) as previously reported. Images were taken with a digital camera Olympus XC50 (Olympus Corporation) at 20×. Digital images from WAT for immunohistochemistry were quantified with FRIDA image analysis software (FRIDA Software; The Johns Hopkins University; MD, USA). Direct detection of GFP fluorescence was performed after perfusion of the animals with FRIDA image analysis software (FRIDA Software; The Johns Hopkins University; MD, USA); briefly, a color mask (pixel threshold masks) was set to define the UCP1 staining. This color mask was applied to all photographs, and the software obtained a numeric value proportional to the color level in each image. These values are represented with respect to control (100%). For the adipocyte area, images were analyzed with ImageJ Software (National Institutes of Health; MD, USA). Direct detection of GFP fluorescence was performed after perfusion of the animals and detected with a fluorescence microscope Olympus IX51, at 4×.

Statistical analysis

For the rat experiments, data are expressed as mean ± s.e.m. (error bars represent s.e.m.), mRNA and protein data were expressed in relation (%) to control (euthyroid, vehicle-treated or GFP) rats. Statistical significance was determined by Student’s t-test when two groups were compared or ANOVA followed by two-tailed Bonferroni post hoc test when more than two groups were compared. P<0.05 was considered statistically significant. For the human studies, statistical analyses were performed using SPSS 12.0 software (IBM). Descriptive results of continuous variables are expressed as mean and s.d. for Gaussian variables or median and interquartile range unless otherwise stated. Parameters that did not fulfill normal distribution were mathematically Log transformed to improve symmetry for subsequent analyses. The relation between variables was analyzed by simple correlation (Pearson’s test and Spearman’s test) and by multivariate regression analysis. Levels of statistical significance were set at P<0.05.

Results

Hyperthyroidism induces browning of WAT in rats

T₄-treated rats exhibited decreased weight gain (Fig. 1A) despite hyperphagia (Fig. 1B). Increased circulating levels of T₄ (Fig. 1C) and T₃ (Fig. 1D), confirmed their hyperthyroid status. Next, we analyzed whether hyperthyroidism induced browning of WAT in these animals. Our mRNA data showed that the mRNA expression of browning markers, such as UCP1, peroxisome proliferator-activated receptor gamma coactivator 1-alpha (PGC1α), CIDEA, PRDM16 and also of uncoupling protein 3 (UCP3) was significantly increased in the gWAT (Fig. 1E) and sWAT (Fig. 1H) of hyperthyroid rats. Histological analysis of WAT showed that hyperthyroid rats exhibited a ‘brown-like’ multilocular pattern, associated with decreased adipocyte area (Fig. 1F and I) and increased UCP1 immunostaining (Fig. 1G and J) in both gWAT and sWAT.

Central T₃ induces browning of WAT in rats

Recent data have shown that the effect of THs on thermogenesis is centrally mediated (Lopez et al, 2010, Alvarez-Crespo et al. 2016). Therefore, we hypothesized that central chronic exposure of T₃ may stimulate browning of WAT. ICV T₃ administration induced a feeding-independent decrease in body weight (Fig. 2A and B). mRNA analysis of gWAT showed tendencies even though statistically non-significant for browning markers to be increased (Fig. 2C). Nevertheless, and more relevant, when histological analyses were assessed, our results were much clearer, indicating that ICV T₃-treated rats displayed a ‘brown-like’ multilocular pattern, associated to decreased adipocyte area (Fig. 2D) and increased UCP1 immunostaining (Fig. 2E).
Figure 1
Effect of hyperthyroidism on WAT browning. (A) Body weight change, (B) daily food intake, (C) T₄ and (D) T₃ circulating levels of euthyroid and hyperthyroid rats. (E and H) mRNA expression of browning markers, (F and I) representative H&E staining (left panels; 20×, scale bar: 100 μm) and adipocyte area (right panels), and (G and J) representative immunohistochemistry with anti-UCP1 antibody showing UCP1 staining (left panels; 20×, scale bar: 100 μm), UCP1 stained area (right panels) in gWAT and sWAT of euthyroid and hyperthyroid rats. Statistical significance was determined by Student’s t-test. N=7 (only for the IHC analyses)-10 animals per group. Error bars represent s.e.m. *, ** and *** P<0.05, 0.01 and 0.001 vs euthyroid.

T₃ in the VMH, but not in the ARC, induces browning of WAT in rats

Next, we aimed to identify the hypothalamic nucleus where T₃ exerted its action on WAT. Therefore, we performed chronic stereotaxic administration of T₃ into the VMH and the neighboring ARC. The correct position of the cannulae was verified by histological examination of coronal sections of the
brains (data not shown). When given into the VMH, T₃ promoted a feeding-independent weight loss (Fig. 3A and B). On the other hand, when T₃ was administered into the ARC, there was a tendency to increase body weight at the end of the treatment, which was associated with hyperphagia (Supplementary Fig. 1A and B). mRNA analysis of gWAT showed significantly increased or clear trends toward increased levels of browning markers when T₃ was delivered within the VMH (Fig. 3C), but not the ARC (Supplementary Fig. 1C). Again, histological analyses confirmed that VMH T₃-treated rats displayed decreased adipocyte area (Fig. 3D) and increased UCP1 immunostaining (Fig. 3E) in gWAT, confirming browning.

**Central effects of T₃ on browning of WAT depend on AMPK in the VMH**

Next, we investigated the molecular mechanisms within the VMH leading to modulation of browning after central T₃ administration. Recent evidence has linked the inhibition of hypothalamic AMPK, and more specifically within the VMH, as a mechanism for the central regulation of BAT thermogenesis by THs (Lopez et al. 2010, 2016, Alvarez-Crespo et al. 2016). Based on this evidence, we hypothesized that the central effect of T₃ on browning might be mediated by specific inhibition of AMPK in the VMH. To test this, adenoviruses encoding either a constitutively active isof orm of AMPKα (AMPKα-CA) or a GFP control vector were injected stereotaxically into the VMH of ICV T₃-treated rats. The AMPKα-CA adenovirus was previously validated (Lopez et al. 2010, Martinez de Morentin et al. 2010, 2012, Whittle et al. 2012, Beiroa et al. 2014, Martins et al. 2016). Overexpression of AMPKα-CA in the VMH, confirmed by GFP immunofluorescence (Fig. 4A), blunted the weight loss caused by central T₃ injection, without alteration in feeding (Fig. 4B and C). Of note, this effect was associated with the reversal of the T₃-induced browning of gWAT, as demonstrated by increased adipocyte area (Fig. 4D) and decreased UCP1 staining (Fig. 4E) in T₃-treated rats receiving AMPKα-CA adenoviruses in the VMH compared with those treated with control GFP adenoviruses. Together, these results are consistent with the observation that AMPK activity in the VMH mediates the central effects of T₃ on browning of WAT.
Browning markers in WAT are positively correlated with circulating T₄ in humans

Finally, we analyzed the relationship between T₄ serum concentrations and the mRNA expression levels of browning marker in sWAT and vWAT, in samples derived from a large cohort of patients. Our data showed that the mRNA levels of UCP1 and CIDEA in sWAT (Fig. 5A and B, Supplementary Fig. 2) and PRDM16 in sWAT and vWAT (Fig. 5C and D), correlated with circulating free T₄, showing a positive association between THs and browning in humans. Multivariate regression analysis indicated that serum free T₄ levels contributed significantly to browning-related (PRDM16, CIDEA and UCP1) mRNA levels variation after controlling for age, gender and BMI (Table 2).

Discussion

In this study, we show that THs induce browning of WAT in rodents and circulating T₄ levels correlate with the expression of browning markers in the WAT of humans. The effect of THs is centrally mediated involving specifically the VMH, a key nucleus modulating energy balance (Morrison et al. 2014, Contreras et al. 2015, Lopez et al. 2016). Notably, this hypothalamic mechanism is mediated through AMPK, which has been described as a key factor regulating the actions of THs at the central level (Lopez et al. 2010, 2016, Alvarez-Crespo et al. 2016).

It has been known for more than a century that THs increase the basal metabolic rate (Magnus-Levy 1895). Typically, most of these effects have been related to the direct actions of THs on metabolically active tissues, such as the liver (Yen 2001), BAT (Bianco et al. 2005, Lopez et al. 2010, Ribeiro et al. 2010, Alvarez-Crespo et al. 2016), heart (Klein & Ojamaa 2001, Kahaly & Dillmann 2005) and skeletal muscle (Short et al. 2001). In those tissues, THs increase metabolic rate and thermogenesis by promoting the generation of energy and also by reducing the thermodynamic efficiency, which lead to heat production and increased temperature (Hulbert & Else 1981, Silva 2006, Lopez et al. 2013).

The process in which precursor cells placed in WAT become beige/brite cells, instead of white adipocytes,
Figure 4
Effect of AMPK overexpression in the VMH and central T3 administration on WAT browning. (A) Bilateral GFP fluorescence in VMH (4×, scale bar 100 μM), (B) body weight change, (C) daily food intake, (D) representative H&E staining (left panels; 20×, scale bar: 100 μm) and adipocyte area (right panels), and (E) representative immunohistochemistry with anti-UCP1 antibody showing UCP1 staining (left panels; 20×, scale bar: 100 μm), UCP1-stained area (right panels) in gWAT of rats stereotaxically treated with GFP or AMPKα-CA adenovirus and ICV treated with vehicle or T3. Statistical significance was determined by ANOVA. N=8 (only for the IHC analyses)-10 animals per group. Error bars represent S.E.M. ** and ***P<0.01 and 0.001 vs vehicle ICV GFP; #, ## and ###P<0.05, 0.01 and 0.001 vs T3 ICV GFP.
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is called browning (Fisher et al. 2012, Shabalina et al. 2013). Consequently, certain WAT depots significantly increase gene expression for UCP1 and their thermogenic capacity (Shabalina et al. 2013). Although the sWAT from the inguinal area is the most classical fat pad where browning studies have been performed, it has also been described in other depots, such as gonadal (Plum et al. 2007, Tews et al. 2013, Neinast et al. 2015, Contreras et al. 2016a, Fulzele et al. 2016, Jia et al. 2016, Lee et al. 2016, Martins et al. 2016, Shao et al. 2016). In this sense, it has been recently demonstrated that when centrally induced, browning affects gWAT in a similar extent to inguinal sWAT (Contreras et al. 2016a, Martins et al. 2016). However, despite the main thermogenic role of central THs, whether they are able to modulate the browning of WAT remains unclear. Here, we show that hyperthyroidism induces browning of WAT (sWAT from the inguinal area and gWAT) in rats. In our hyperthyroid model, T_4 was administered peripherally, which might imply the existence of direct effects of THs on white adipocytes, known to express TRs (Brent 2012, Lopez et al. 2013, 2016, Alvarez-Crespo et al. 2016). Alternatively, THs may exert a central action after crossing the blood-brain barrier (BBB), which would be in agreement with recent evidence from our group, demonstrating that the metabolic effects of THs on brown fat are centrally mediated (Lopez et al. 2010, Alvarez-Crespo et al. 2016). Therefore, we investigated the contribution of the central effects of THs on browning of WAT. Our data show that, when administered centrally, T_3 promotes a similar pattern of browning of WAT as observed in the hyperthyroid model. Remarkably, the central action of T_3 targets one particular hypothalamic nucleus, the VMH. Indeed, stereotaxic administration of the hormone into the ARC (a neighboring nucleus) did not recapitulate the effects on the browning program induced by T_3 within the VMH. Considering that the VMH also plays a major role in the modulation of BAT function via THs (Lopez et al. 2010, 2013, 2016, Alvarez-Crespo et al. 2016), our data suggest that this hypothalamic site is a key modulator of both white and brown fat activity.

Current evidence has demonstrated that inhibition of AMPK in the VMH plays a major role in mediating either the actions of THs on BAT (Lopez et al. 2010, 2013, 2016, Alvarez-Crespo et al. 2016) or the browning of WAT, for example by glucagon-like peptide 1 (GLP-1) agonism (Beiroa et al. 2014). To elucidate the contribution of hypothalamic AMPK activity on the browning of WAT by THs, we genetically activated AMPK in the VMH of rats centrally treated with T_3. Our data showed that activation of AMPK totally blunted the effects of T_3 on WAT browning. Interestingly, this action was associated with a feeding-independent recovery of body mass, which was reduced by central T_3. This evidence suggests that the augmented thermogenic capacity of brite adipocytes

Figure 5
Correlation between T_4 circulating levels and browning markers in human WAT. Correlation between UCP1 (A), CIDEA (B) and PRDM16 (C) in sWAT and PRDM16 in vWAT (D) in human subjects.
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Table 2 Multivariate regression analyses to predict sWAT CIDEA, PRDM16 and UCP1 and vWAT PRDM16 gene expression in the human cohort.

<table>
<thead>
<tr>
<th></th>
<th>sWAT CIDEA</th>
<th>sWAT PRDM16</th>
<th>sWAT UCP1</th>
<th>vWAT PRDM16</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (years)</td>
<td>β</td>
<td>P</td>
<td>β</td>
<td>P</td>
</tr>
<tr>
<td>-0.16</td>
<td>0.15</td>
<td></td>
<td>-0.14</td>
<td>0.28</td>
</tr>
<tr>
<td>Sex</td>
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<td>0.63</td>
<td>-0.01</td>
<td>0.92</td>
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<tr>
<td>BMI (kg/m²)</td>
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<td>0.04</td>
<td>-0.17</td>
<td>0.19</td>
</tr>
<tr>
<td>Serum free T₄ (pmol/L)</td>
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<td>0.03</td>
<td>0.35</td>
<td>0.01</td>
</tr>
<tr>
<td>Adjusted R²</td>
<td>0.096</td>
<td>(9.6%)</td>
<td>0.105</td>
<td>(10.5%)</td>
</tr>
<tr>
<td>P (model)</td>
<td>0.018</td>
<td></td>
<td>0.04</td>
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β corresponds to the standardized beta coefficient of the multiple regression analyses. Bold indicates statistical significance.

(Shabalina et al. 2013) participates together with the BAT-mediated action in the weight-reducing effects of central T₃.

Finally, we aimed to investigate whether browning markers correlate with circulating THs levels in humans. Remarkably, our results indicate that serum levels of T₄ are positively associated with UCP1, CIDEA and PRDM16 in WAT. To our knowledge, this is the first demonstration that THs modulate WAT browning in humans. Whether increased WAT browning is observed in hyperthyroid patients is not reported, but considering that THs also stimulate BAT in humans (Lahesmaa et al. 2014) and that most of the human BAT is actually beige fat (Jespersen et al. 2013, Shinoda et al. 2015), it is tempting to speculate that browning of WAT may account for the increased energy expenditure that characterizes hyperthyroidism (Warner & Mittag 2012, Lopez et al. 2013). In this sense, we have performed some preliminary studies in hyperthyroid patients and detected a trend in the correlation between UCP1 mRNA expression and T₄; however, further work will be necessary to properly investigate this association. If that is the case, strategies to modulate browning might be of therapeutic benefit in controlling the effects of thyrotoxicosis. This latter possibility is particularly relevant in the context of life-threatening conditions, such as thyroid storm, for which current treatments are not satisfactory. In addition, the induction of browning by TR agonism might be a suitable strategy for the treatment of obesity. In this regard, recent data have shown that treatment with the TR agonist GC-1 promotes browning of WAT and ameliorates obesity and diabetes in mice (Lin et al. 2015). In summary, our results make evident the importance of THs in the browning of WAT in rodent and humans. This observation provides new insights into the physiological effects of THs and also in the pathogenesis of hyperthyroidism-induced effects on energy balance; it also suggests potential therapeutic strategies to counteract this disorder or other catabolic states.

Supplementary data
This is linked to the online version of the paper at http://dx.doi.org/10.1530/JOE-16-0425.

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.

Funding
The research leading to these results has received funding from the European Community’s Seventh Framework Programme (FP7/2007–2013) under grant agreement n° 281854 – the ObeRStress project (M L), Xunta de Galicia (R N: 2015-CP080 and PIE13/00024; M L: 2015-CP079), MINECO co-funded by FEDER (R N: BFU2015-70664-R; C D: BFU2014-55871-P; M L: SAF2015-71026-R and BFU2015-70454-FEDER/Adipoplast). CIBER de Fisiopatología de la Obesidad y Nutrición is an initiative of ISCIII. The funders had no role in study design, data collection and analysis, decision to publish or in the preparation of the manuscript.

Author contribution statement
N M-S, J M M-N, C C and E R-P performed the in vivo experiments (hormonal, drug and viral treatments) and the analytical methods (real-time quantitative PCR and immunohistochemistry). N M-S, J M M-N, J F, R N, C D, J M F-R and M L designed the experiments, analyzed, discussed and interpreted the data. N M-S, J M M-N and M L made the figures. M L developed the hypothesis, coordinated and directed the project and had final approval of the submitted manuscript.

Acknowledgements
The authors thank Patricia Seoane-Collazo and Ismael González-García (University of Santiago de Compostela) for their comments and criticisms.

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Received in final form 20 November 2016
Accepted 2 December 2016
Accepted Preprint published online 2 December 2016