Comparative Secretome Analyses of Primary Murine White and Brown Adipocytes Reveal Novel Adipokines

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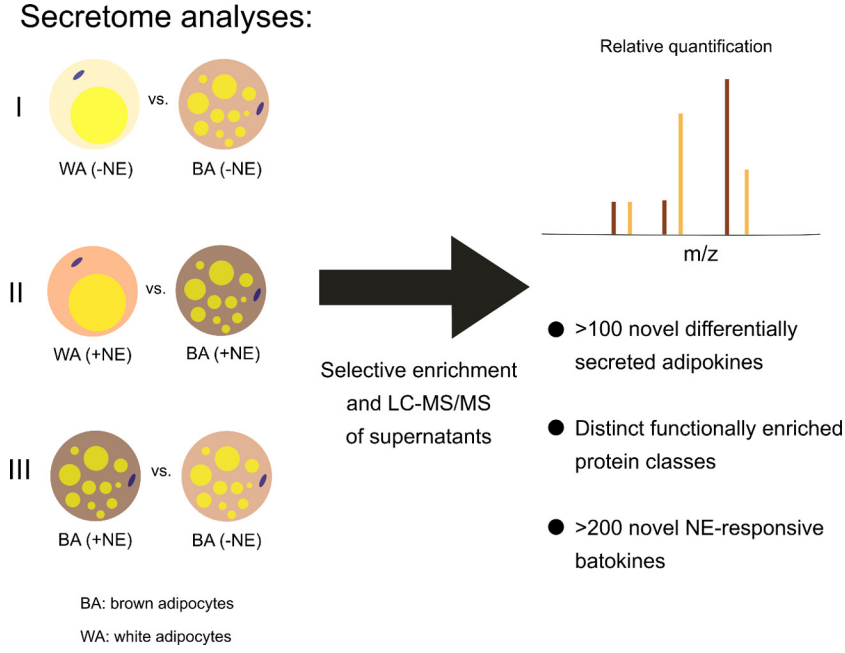
In Brief

The secretome of white and brown primary murine adipocytes, with and without stimulation with norepinephrine (NE), has been determined by using mass spectrometry combined with AHA labeling and pulsed SILAC. The results reported reveal a comprehensive catalogue of novel adipokines secreted from white and brown adipocytes and responsive to NE. Given the beneficial effects of brown fat activation on systemic metabolism and its endocrine function, this study provides an archive of potential brown adipokines and biomarkers for activated brown fat.

Graphical Abstract



Highlights

- First comparative proteomic analysis of white and brown adipocyte secretomes.
- 100 novel adipokines differentially secreted from white *versus* brown adipocytes.
- Functionally enriched protein class changes in white and brown adipocytes.
- 200 novel, NE-responsive adipokines from brown adipocytes.

Ali Khan et al., 2018, Molecular & Cellular Proteomics *17*, 2358–2370

https://doi.org/10.1074/mcp.RA118.000704

Comparative Secretome Analyses of Primary Murine White and Brown Adipocytes Reveal Novel Adipokines*[S]

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The adipose organ, including white and brown adipose tissues, is an important player in systemic energy homeostasis, storing excess energy in form of lipids while releasing energy upon various energy demands. Recent studies have demonstrated that white and brown adipocytes also function as endocrine cells and regulate systemic metabolism by secreting factors that act locally and systemically. However, a comparative proteomic analysis of secreted factors from white and brown adipocytes and their responsiveness to adrenergic stimulation has not been reported yet. Therefore, we studied and compared the secretome of white and brown adipocytes, with and without norepinephrine (NE) stimulation. Our results reveal that carbohydrate-metabolism-regulating proteins are preferably secreted from white adipocytes, while brown adipocytes predominantly secrete a large variety of proteins. Upon NE stimulation, an increased secretion of known adipokines is favored by white adipocytes while brown adipocytes secreted higher amounts of novel adipokines. Furthermore, the secretory response between NE-stimulated and basal state was multifaceted addressing lipid and glucose metabolism, adipogenesis, and antioxidative reactions. Intriguingly, NE stimulation drastically changed the secretome in brown adipocytes. In conclusion, our study provides a comprehensive catalogue of novel adipokine candidates secreted from white and brown adipocytes with many of them responsive to NE. Given the beneficial effects of brown adipose tissue activation on its endocrine function and systemic metabolism, this study provides an archive of novel batokine candidates and biomarkers for activated brown adipose tissue. ***Molecular & Cellular Proteomics 17: 2358–2370, 2018. DOI: 10.1074/mcp.RA118.000704.***

The adipose organ has an important role in regulating fatty acid and glucose metabolism for whole-body energy homeostasis. In mammals, this is mediated by two distinct types of adipose tissues: white adipose tissue (WAT), which is specialized in the storage of lipids upon energy surplus and in lipid release upon energy deprivation, and brown adipose tissue (BAT), which is able to dissipate energy in the form of heat, called nonshivering thermogenesis, upon adrenergic stimulation. Both tissue types are essential for metabolic health, as disruption of normal WAT function leads to insulin resistance (1, 2), while the activation of BAT increases glucose uptake, thus leading to decreased blood glucose levels, improved insulin sensitivity, and weight loss (3, 4).

WAT is also widely recognized as an endocrine organ owing to the discovery of several adipose-tissue-specific secreted proteins called adipokines. These include leptin that controls satiety and body weight, adiponectin that increases insulin sensitivity, and resistin that contributes to insulin resistance and that has a proinflammatory effect (5–7). However, BAT, unlike its white counterpart, has just emerged as an endocrine tissue (8). Interestingly, mice completely lacking BAT became obese while mice only deficient in UCP1 became cold sensitive but not obese (9, 10). These studies suggest that BAT can affect whole-body energy homeostasis by UCP1-dependent and independent mechanisms involving "brown adipokines" or "batokines." Indeed, recent studies in mice and rats have identified the first brown adipokine candidates with autocrine, paracrine, and endocrine functions, including vascular endothelial growth factor-A, insulin-like growth factor I (IGF-I), fibroblast growth factor-2, fibroblast growth factor-21, neuregulin 4, triiodothyronine, interleukin 6, and bone morphogenetic protein 8b (11). These factors have various functions like promoting angiogenesis (vascular endothelial growth factor-A) or increasing sensitivity to adrenergic stimulation (bone morphogenetic protein 8b) (11). However, a comprehensive and comparative proteomic analysis in pri-

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Received March 24, 2018, and in revised form, August 6, 2018
Published, MCP Papers in Press, August 22, 2018, DOI 10.1074/mcp.RA118.000704

mary murine white and brown adipocytes, including stimulation with norepinephrine (NE), a catecholamine that triggers essential physiological responses in adipose tissues, has not been reported so far.

Therefore, in this study, we investigated the secretome of stroma-vascular fraction (SVF)-derived murine white and brown adipocytes by using mass spectrometry combined with click-chemistry and pulsed stable isotope labeling with amino acids in cell culture (pSILAC). We conducted three comparative analyses: the first two compared the secretome of white and brown adipocytes without and with NE treatment, respectively, while the third experiment compared brown adipocytes with and without NE stimulation. We found that white adipocytes predominantly secrete carbohydrate-metabolism-regulating proteins, while brown adipocytes preferentially secrete integrin-signaling proteins. With NE stimulation, this secretory signature in white adipocytes changed to more secreted proteins involved in lipid metabolism, while in brown adipocytes the secretory profile shifted more to specific proteins with anti-inflammatory properties. When comparing this NE-stimulated to the unstimulated (basal) state, the secretory profile between white and brown adipocytes became complex targeting lipolysis, glucose uptake, browning of white adipocytes, and protection against oxidative stress. Moreover, in brown adipocytes, NE stimulation broadly and significantly altered the adipocyte secretome. In conclusion, our study provides a comprehensive insight into the secretome of white and brown adipocytes with numerous novel adipokine candidates, in part also responsive to NE.

EXPERIMENTAL PROCEDURES

Isolation, Culturing, and Adipocyte Differentiation of Murine SVF Cells—Mouse primary preadipocytes were isolated from 8-week-old male C57BL/6J mice (Charles River Laboratories, Inc., Charleston). The inguinal WAT and interscapular BAT were excised and placed in ice-cold 1X D-PBS (Gibco, Schwerte, Germany). Next, the organs were cleaned by removing the lymph nodes from WAT and residual WAT from BAT. Both adipose tissues were minced and digested in collagenase. WAT was digested in DMEM-based collagenase solution consisting of 1.5 mg/ml collagenase II (Sigma, Steinheim, Germany) and 0.5% bovine serum albumin (Sigma) while BAT was digested with additional 15 mM HEPES (Gibco), 3.2 mM $CaCl_2$, and 10% FBS at 37 °C, centrifuged at 100 rpm until no tissue clumps were visible (less than an hour). The digestion solution was centrifuged at 1,000 rpm for 5 min, and the pellet was resuspended in DMEM growth media (10% FBS, 1% Pen/Strep) and passed through a 70 μm nylon filter (Fisher Scientific, Schwerte, Germany). The cells were plated on 12-well plates, and differentiation was started after the cells reached confluency by the addition of 1 mg/ml insulin, 0.5 mM 3-isobutyl-1-methylxanthine (IBMX), 0.25 mM dexa-methasone, and 1/1,000 volume ABP (50 mg/ml L-ascorbate, 1 mM biotin, 17 mM pantothenate) in high (4.5 g/l) glucose DMEM containing 10% FCS and 1% Pen/Strep. 1 nM of triiodothyronine was added additionally for differentiating brown preadipocytes. The same media were added on day 2 and only insulin and ABP (triiodothyronine for brown adipocytes) were added on day 4. Starting day 6 of differentiation DMEM growth medium (10% FBS, 1% Pen/Strep) was added to the cells.

Measurement of Cell Death—The cytotoxic effect of L-azidohomoalanine (AHA)[1]-supplemented media on primary adipocytes was measured using the Cytotoxicity Detection Kit (LDH) (Roche, Mannheim, Germany) based on the manufacturer's instructions. Fresh growth medium was taken as blank, and adipocytes treated with 1% Triton X-100 (Sigma) was the positive control. The percentage of cell death or LDH release was depicted as % LDH compared with the positive control (100% cell death).

Measurement Leptin and Resistin Concentrations in Cellular Supernatant Using MILLIPLEX® MAP Mouse Metabolic Hormone Panel—The MILLIPLEX® MAP Mouse Metabolic Hormone panel (Cat. # MMHMAG-44K) was used with the Luminex xMAP® platform (MAGPIX®) to detect leptin and resistin in tissue culture supernatant from primary adipocytes. The immunoassay procedure was carried out according to the manufacturer's instructions and was analyzed on the MAGPIX® with the xPONENT software. The mMedian fluorescent intensity data were analyzed using a five-parameter logistic method for calculating the concentrations of leptin and resistin in the samples.

Experimental Design and Statistical Rationale—We performed the comparative secretome studies by combining AHA and pSILAC labeling (12). This involved concomitant pulse-labeling of the cell population with AHA, an azide-bearing analog of methionine, and stable isotope-labeled amino acids. AHA allows the enrichment (by selective and covalent capture) of newly synthesized AHA-containing proteins using an alkyne-activated resin via click-chemistry. SILAC was then used to quantitatively compare secretome composition of cells between two different conditions. The resultant secreted proteome obtained by the combination of these two techniques was analyzed using mass spectrometry (Fig. 1).

Specifically, to deplete cells of methionine, lysine, and arginine, the cells were incubated for 30 min in depletion medium (DMEM non-GMP formulation without methionine, arginine, and lysine; GIBCO) with 10% FBS (GIBCO) before incubation in the same medium supplemented with 0.1 mM l-AHA (AnaSpec, Inc.) and either 84 μg/ml [13C6,15N4] l-arginine and 146 μg/ml [13C6,15N2]l-lysine or 84 μg/ml [13C6]l-arginine and 146 μg/ml [4,4,5,5-D4]l-lysine (Cambridge Isotope Laboratories, Inc., Tewksbury). The cells were either stimulated for 24 h with 0.5 μM NE (Sigma) or not, along with the labeled amino acid media. The supernatants were collected from a row of four wells of a 12-well plate and pooled together as one replicate. There were three replicates for each analysis, and the third replicate in each analysis was reciprocally labeled compared with the first two. Collected supernatant samples were centrifuged (5 min at 1,000 *g*), cOmplete™ EDTAfree protease inhibitor (Roche) was added, and the mixture was frozen at −80 °C. DNA was extracted from the cells left behind on the plate and used to normalize the mixing of the collected media before the enrichment.

Enrichment of Newly Synthesized Proteins and On-bead Digestion—Newly synthesized proteins from concentrated media (Amicon Ultra® Centrifugal Filters, 3-kDa cutoff, Millipore) (250 μl) were enriched using the Click-iT® Protein Enrichment Kit (Invitrogen, Schwerte, Germany), applying the vendor's protocol with slight modifications, as described previously (12). One-hundred microliters of agarose resin slurry were used, and the volumes of all reagents were divided by two. After washing the resin with 900 μl water, the concentrated media, diluted in 250 μl urea buffer, and catalyst solution were added and incubated for 16–20 h at room temperature. After washing the resin with 900 μl water, 0.5 ml SDS buffer, and 0.5 μl

[1] The abbreviations used are: AHA, L-azidohomoalanine; BAT, brown adipose tissue; ECM, extracellular matrix; GO, gene ontology; pSILAC, pulsed stable isotope labeling with amino acids in cell culture; NE, norepinephrine; SVF, stroma vascular fraction; WAT, white adipose tissue.

1 M dithiothreitol (Bio-Rad, Munich, Germany) were added and vortexed at 70 °C for 15 min. The supernatant was aspirated, and 3.7 mg iodoacetamide (Bio-Rad) were added and incubated for 30 min in the dark.

The resin was transferred to a spin column (supplied with the kit) and washed with 20 ml of SDS buffer, 20 ml of 8 M urea in 100 mM Tris, pH 8, 20 ml of 20% isopropanol, and 20 ml of 20% acetonitrile. After dissolving the resin in digestion buffer (100 mM Tris, pH 8, 2 mM $CaCl_2$, and 10% acetonitrile), 0.5 μg trypsin (Promega) were added and incubated overnight at 37 °C. The peptide solution was collected, and the resin was washed with 500 μl water. Both solutions were combined and acidified with 20 μl 10% CF_3COOH.

Sample Preparation for Mass Spectrometry—The acidified samples were desalted using Sep-Pak® cartridges (Vac 1 cc (50 mg) tC18, Waters, Eschborn, Germany) and fractionated (into 12 fractions) using isoelectric focusing on an Agilent 3100 OFFGEL Fractionator in combination with Immobiline® DryStrips (ph 3–10 NL, 13 cm, GE Healthcare, Freiburg, Germany). Focusing was performed at a constant current of 50 mA with a maximum voltage of 4,000 V. After reaching 20 kVh, the samples were collected, acidified with CF_3COOH, and desalted using StageTips (13). The peptide samples were dried and dissolved in 4% acetonitrile, 0.1% formic acid.

LC-MS/MS—Peptides were separated using a nanoAcquity ultra-performance liquid chromatography (UPLC) system (Waters) fitted with a trapping (nanoAcquity Symmetry C_{18}, 5 μm, 180 μm $\times$ 20 mm) and an analytical column (nanoAcquity BEH C_{18}, 1.7 μm, 75 μm $\times$ 200 mm). The outlet of the analytical column was coupled directly to an Orbitrap Velos Pro (Thermo Fisher Scientific) using a Proxeon nanospray source (solvent A, 0.1% formic acid; solvent B, acetonitrile and 0.1% formic acid). The samples were loaded with a constant flow of solvent A at 15 μl per min onto the trapping column. Peptides were eluted through the analytical column at a constant flow of 0.3 μl per min. During the elution step, the percentage of solvent B increased in a linear fashion from 3% to 25% in 110 min, which was followed by an increase to 40% in 10 min and an increase to 85% in 1 min. The peptides were introduced into the mass spectrometer by a Pico-Tip Emitter 360 μm outer diameter $\times$ 20 μm inner diameter; 10 μm tip (New Objective). Full scan mass spectrometry spectra with mass range 300–1,700 mass-to-charge ratio (*m/z*) were acquired in profile mode in the Orbitrap with a resolution of 30,000. The filling time was set at maximum of 500 ms with a limitation of 10^6 ions. The most intense ions (up to 15) from the full-scan mass spectrometry were selected for fragmentation in the LTQ. A normalized collision energy of 40% was used, and the fragmentation was performed after accumulation of 3 $\times$ 10^4 ions or after a filling time of 100 ms for each precursor ion (whichever occurred first). MS/MS data were acquired in centroid mode. Only multiply charged (2+ or 3+) precursor ions were selected for MS/MS. The dynamic exclusion list was restricted to 500 entries, with a maximum retention period of 30 s and a relative mass window of 10 ppm. Lock mass correction using a background ion (*m/z* 445.12003) was applied.

Data Processing—The mass spectrometric raw data were processed using MaxQuant (version 1.3.0.5) (14) and MS/MS spectra were searched using the Andromeda search engine (15) against mouse (75,721 entries, downloaded 20.02.2013) proteins in UniProt, concatenated to the bovine-specific portion of UniProt (26,526 entries, downloaded 21.06. 2011), to which 247 frequently observed contaminants and reversed sequences of all entries had been added. Enzyme specificity was set to trypsin/P, and a maximum of two missed cleavages were allowed. Cysteine carbamidomethylation was used as the fixed modification, and methionine oxidation, protein N-terminal acetylation, and replacement of methionine by AHA were used as variable modifications. The minimal peptide length was set to six amino acids. The initial maximal allowed mass tolerance was set to 20 ppm for peptide masses and then was set to 6 ppm in the main search and to 0.5 Da for fragment ion masses. False discovery rates for peptide and protein identification were set to 1%. At least one unique peptide was required for protein identification. The protein identification was reported as an indistinguishable "protein group" if no unique peptide sequence to a single database entry was identified.

For protein quantification, a minimum of two ratio counts was set and the "requantify," and "match between runs" functions were enabled. A protein group was kept for further analysis if it contained at least one mouse sequence and the number of identified peptide species carrying an intermediate or heavy label divided by the total number of peptide species detected in the complete experimental setup was higher than 0.2. Data are available via ProteomeXchange (16) with the identifier PXD009280.

Statistical Analysis—Only proteins that have been quantified in at least two of the three replicates have been used for statistical analysis. In a first standardization step, the $\log_2$ distributions of available protein ratios per replicate sample have been centered around zero. Then a linear model has been fitted to those centered data, which was subjected to an empirical Bayes moderated *t* test using the Limma package (version 3.30.13) in R/Bioconductor (version 3.3.2) (17). In order to fully embrace the potential of the presented datasets and to give a complete picture of differential secretion, we report the default output of adjusted *p* values implemented in LIMMA. This *p* value adjustment controls false discovery rates and is based on Benjamini and Hochberg's method. Proteins with an adjusted *p* value of less than 0.05 were considered to be differentially secreted, and those results should be interpreted in a way that within the group of differentially secreted proteins a fraction of 5% is expected to be false discoveries. Data visualization was performed with the ggplot2 package (version 2.2.1) and included annotations derived from Gene Ontology (GO).

GO Enrichment Analysis—The enrichment analysis for GO annotation terms was performed using DAVID Bioinformatics Resources 6.8 (https://david.ncifcrf.gov/home.jsp) (18). The background set was all the differentially secreted proteins in the particular secretome analysis. The *p* value cutoff for the GO enrichment was 0.1 (EASE 0.1).

RESULTS

White Adipocytes Secrete More Proteins Involved in Carbohydrate Metabolism While Brown Adipocytes Secrete More Extracellular Matrix Proteins—We were interested in how the secretome of primary murine white and brown adipocytes changes upon stimulation with NE. We investigated this by performing comparative secretome studies using a combination of AHA and pSILAC labeling (Fig. 1) (12). In total, we identified 1,337 unique proteins in three different analyses that showed detectable signals in at least one condition (supplemental Table 1*A*) and 499 unique proteins that showed detectable signals in at least two (supplemental Table 1*B*). For all subsequent analyses, the latter list of 499 proteins was used.

In the first analysis, we compared the secretome of white and brown adipocytes at basal conditions (*i.e.* without NE stimulation) and obtained 141 significantly differentially secreted proteins (p-adj < 0.05, nominal p value cutoff $= 0.023$, Fig. 2*A*, supplemental Table 2). As adipocytes secrete a number of known secreted factors called adipokines, we first investigated whether we can identify known adipokines as positive controls. Indeed, we were able to identify well-known

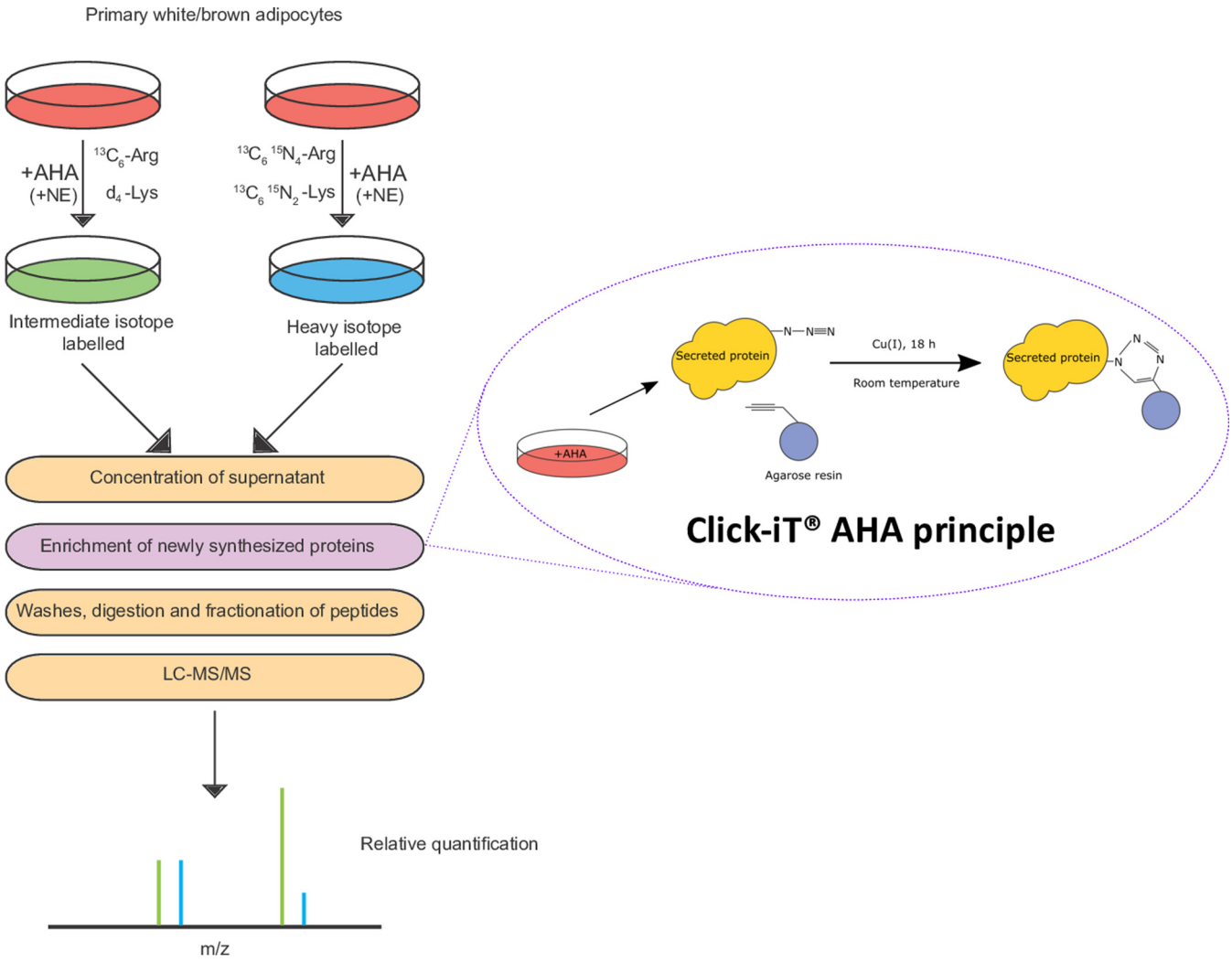

FIG. 1. **Principle and experimental design of the secretome analysis**. The secretome analysis workflow started with incubation of primary white or brown adipocytes with media lacking methionine, lysine, and arginine for 30 min followed by media supplemented with AHA and either intermediate or heavy isotope labeled amino acids (lysine and arginine) for 24 h. In addition, 0.5 μM NE was added in selected analyses. After incubation, the supernatants were collected and the secreted (AHA-containing) proteins were enriched via click-chemistry, washed, digested, fractionated, and analyzed by LC-MS/MS.

classical adipokines like adipsin (complement factor D), adiponectin, and resistin. In addition, we also found lesser-known adipokines like sparc-like 1, spondin-1, dermatopontin, C-C motif chemokine 8, and matrix metalloproteinase-14 (Fig. 2*A*), thus supporting the validity of our approach. Spondin-1showed a fivefold increased secretion in white adipocytes and was the highest differentially secreted protein from white adipocytes. It was first identified as adipokine secreted from white adipocytes in rats, and its secretion was shown to be regulated by insulin resistance (19). In addition, it has been suggested to promote growth and guidance of the axons (20). All these adipokines exhibited a more pronounced secretion in white adipocytes, but interestingly, they were also secreted from brown adipocytes. Moreover, we also found two other adipokines, collagen alpha-2(I) chain and collagen alpha-2(V) chain, known to be secreted from 3T3-L1 white adipocytes during adipogenesis, to be fourfold and twofold higher secreted from brown compared with white adipocytes, respectively. Thus, this analysis demonstrated that a number of well-known white-adipocyte-derived adipokines are also, if not even higher, secreted from brown adipocytes.

Next, we were interested in associating unique biological processes to the secreted proteins. Thus, we applied GO term enrichment analysis to the significantly differentially secreted proteins. This enrichment analysis yielded "Carbohydrate metabolic process" as the most enriched GO term for the proteins with increased secretion from white adipocytes (Fig. 2*B*, *upper panel*, supplemental Table 3), confirming one of their main functions being the storage of excess carbohydrates in the form of triglycerides. Proteins enriched in this term include glyceraldehyde-3-phosphate dehydrogenase, and insulin-like growth factor 2 (IGF2) (Fig. 2*C*). "Oxidation-

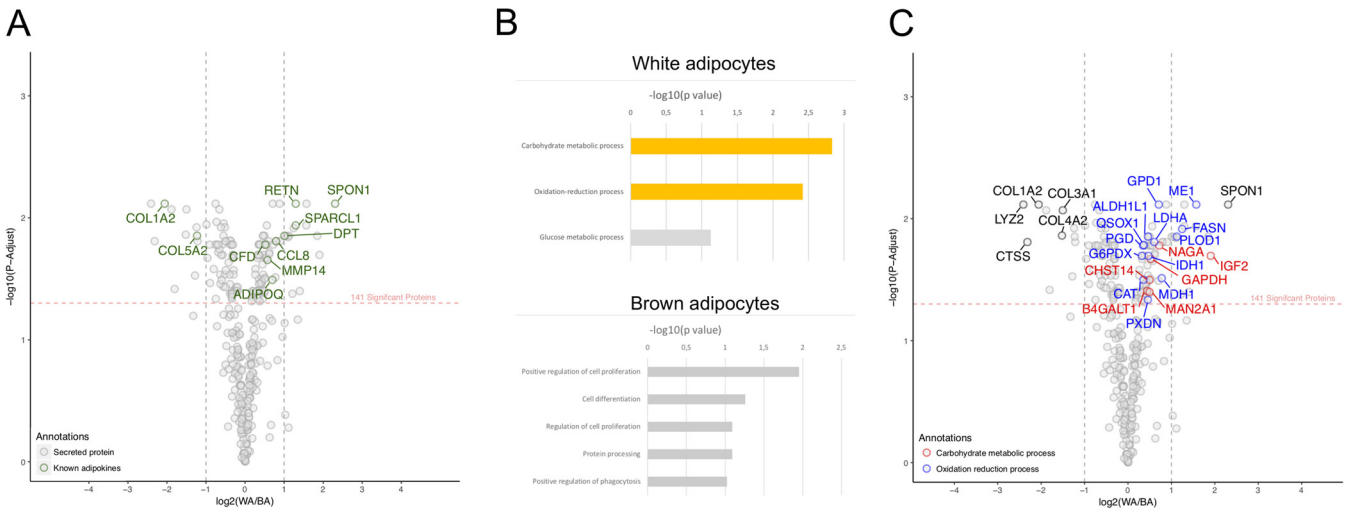

FIG. 2. **Comparative secretome analysis between primary murine white and brown adipocytes.** *A*. Volcano plot depicting 141 significantly (p.adj < 0.05, nominal p value cutoff $= 0.023$) differentially secreted proteins including 10 known adipokines (in green). *B*. GO enrichment analysis of the 141 proteins based on their higher secretion in white or brown adipocytes, with significantly enriched GO terms in color (p value threshold of 0.01) and nonsignificant ones in gray (p value threshold of 0.1). *C*. Volcano plot as in panel *A*. Proteins belonging to the enriched GO terms are named and colored. Additionally, the top differentially secreted proteins that are discussed in the results are labeled in black. WA: white adipocytes, BA: brown adipocytes.

reduction" process was the second GO term enriched and included the proteins catalase and fatty acid synthase. Catalase, a potent antioxidant enzyme, correlates in expression levels with adipogenesis in a peroxisome proliferator-activated receptor (PPAR)γ-dependent manner (21) while the secretion of fatty acid synthase, a key enzyme in *de novo* lipogenesis, is increased during nutrient deprivation by AMP-activated protein kinase (AMPK) activation (22). Interestingly, no GO term was significantly enriched for proteins preferentially secreted from brown adipocytes indicating a broader range of secreted protein classes.

The majority of identified factors were not known to be secreted by either white or brown adipocytes, thus they have not been recognized as potential adipokines before. The two most highly secreted proteins from the brown adipocytes were Lysozyme C-2 (LYZ2) and cathepsin S (CTSS) (Fig. 2*C*). These catalytic enzymes are both components of the extracellular matrix (ECM), with CTSS exhibiting pro-inflammatory properties (23). Interestingly, other highly secreted proteins from brown adipocytes were collagen α1 and α2 chains belonging to type I, III, and IV collagen fibers (Fig. 2*C*). This indicates that brown adipocytes preferentially secrete higher amounts of ECM proteins compared with white adipocytes.

NE Triggers an Increased Secretion of Classical Known Adipokines in White Adipocytes and of Novel Adipokines in Brown Adipocytes—The sympathetic nervous system tightly regulates the function of WAT and BAT via NE. This neurotransmitter is a potent stimulant for adipocytes: it primarily activates lipolysis in white adipocytes and thermogenesis in brown adipocytes as well as brown-like characteristics during adipogenesis. However, as the NE-induced secretory response of adipocytes has not been established yet, we investigated how the NE-induced secretome differs between white and brown adipocytes. We treated SVF-derived differentiated primary white and brown adipocytes with NE for 24 h and obtained 186 significantly differentially secreted proteins (p-adj < 0.05, nominal p value cutoff $= 0.024$, Fig. 3*A*, supplemental Table 5). Among this large number of secreted proteins, we detected the aforementioned adipokines similar to the first analysis (Fig. 3*A*). In addition, we found three proteins to be responsive to NE, known to be secreted from white adipocytes, *i.e.* osteopontin (SPP1) that promotes inflammation and macrophage infiltration in adipose tissue, lipoprotein lipase that hydrolyzes triglycerides from chylomicrons, and very low density lipoproteins, and ectonucleotide pyrophosphatase/phosphodiesterase family member 2 that catalyzes the formation of lysophosphatidic acid in extracellular fluids (24–26) (Fig. 3*A*). However, in addition to these known adipokines, there were several adipokine candidates not known so far to be secreted by white or brown adipocytes upon NE treatment.

GO enrichment analysis revealed that the overall profile of the NE-induced secretome of white and brown adipocytes was very different (Fig. 3*B*, supplemental Tables 6 and 7). Surprisingly, the GO term "Tricarboxylic acid" was enriched among the proteins that were more secreted from white than from brown adipocytes. This term included proteins like isocitrate dehydrogenase 1 and aconitase 2, indicating a possible novel function outside their primary location in the cytosol or mitochondria. Similar to the previous analysis (Fig. 2*B*, *lower panel*), and despite the large number of significantly differentially secreted proteins no GO term for biological processes was enriched among the proteins favoring higher secretion

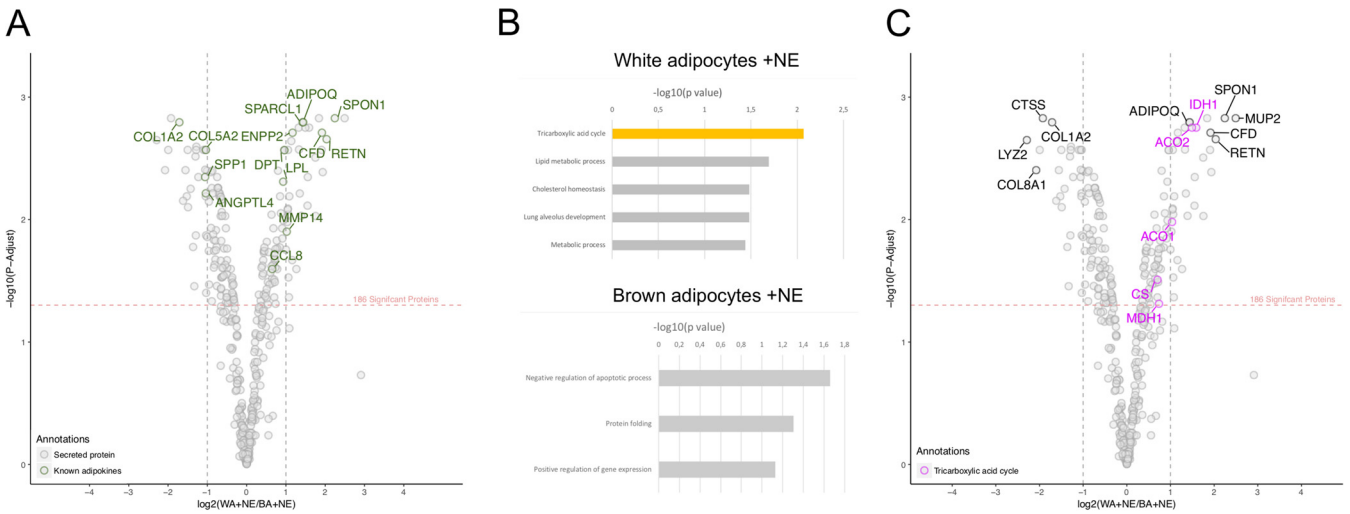

FIG. 3. **Comparative secretome analysis between primary murine white and brown adipocytes upon NE stimulation.** *A*. Volcano plot depicting 186 significantly (p.adj < 0.05, nominal p value cutoff $= 0.023$) differentially secreted proteins including 14 known adipokines (in green). *B*. GO enrichment analysis of the 186 proteins based on their higher secretion in white or brown adipocytes, with significantly enriched GO terms in color (p value threshold of 0.01) and nonsignificant ones in gray (p value threshold of 0.1). *C*. Volcano plot as in panel *A*. Proteins belonging to the enriched GO terms are named and colored. Additional top differentially secreted and discussed proteins are named in black. WA: white adipocytes, BA: brown adipocytes.

from brown adipocytes, again indicating a broad secretory response from brown adipocytes.

In response to NE, the most differentially secreted protein from white compared with brown adipocytes was major urinary protein 2 with a 5.6-fold change. Major urinary protein 2 is a novel adipokine candidate, belonging to the family of major urinary proteins that are known to regulate glucose and lipid metabolism and increase energy expenditure (27, 28) (Fig. 3*C*). Spondin-1 and resistin were the second and third most differentially secreted proteins with fivefold and fourfold higher secretion from white compared with brown adipocytes, respectively. Other well-known adipokines like adipsin and adiponectin were also among the highest differentially secreted proteins (Fig. 3*C*). Thus, the majority of the proteins with highest secretion in white compared with brown adipocytes upon NE treatment were well-known adipokines.

In response to NE in brown adipocytes, we identified lysozyme C-2, collagen alpha-1(VIII) chain (COL8A1), chemokine (C-C motif) ligand 9 (CCL9), cathepsin S, and collagen alpha-2(I) chain as novel and highest secreted proteins compared with white adipocytes (Fig. 3*C*). Thus, lysozyme C-2, cathepsin S, and collagen alpha-2(I) chain were more highly secreted from brown adipocytes, with and without NE stimulation. Chemokine (C-C motif) ligand 9 is a unique member of the CC chemokine family that promotes preadipocyte recruitment and modulates adipogenesis in white adipocytes (29). However, the physiological implications of its fourfold higher secretion upon NE treatment from brown adipocytes compared with white adipocytes needs further investigation. Collagen alpha-1(VIII) chain (COL8A1), including the vastatin fragment, was also secreted fourfold higher from NE-treated brown adipocytes than white adipocytes (Fig. 3*C*). We speculate that the increased secretion of collagen alpha-1(VIII) chain upon NE treatment in brown adipocytes promotes proliferation and adipogenesis via PI3K/AKT signaling (30, 31). Other novel adipokines that showed threefold increased secretion in this condition were heme oxygenase 1 and beta-nerve growth factor (supplemental Table 5). We summarize that, in white adipocytes, the top secreted proteins upon NE stimulation are well-known classical adipokines, while in brown adipocytes, novel adipokine candidates are the top secreted proteins.

The Secretory Response Between NE-stimulated and Basal State is Complex Involving Lipolysis, Glucose Uptake, Browning of White Adipocytes, and Protection Against Oxidative Damage—In addition to the comparative secretome analyses between white and brown adipocytes (*i.e.* Figs. 2*A* and 3*A*), we were also interested in proteins whose secretion was significantly altered upon NE treatment compared with the unstimulated state. For this purpose, we analyzed the combined data of the significantly differentially secreted proteins from the two analyses above (Fig. 4). The combination of two independent variables, the type of adipocyte and stimulation with NE, led to the division of the scatterplot into four quadrants: Q1-Q4. Proteins, which do not change in secretion upon NE treatment compared with the unstimulated state or change in secretion to a similar degree between white and brown adipocytes, are along the diagonal.

In Q1, the aforementioned adipokines adipsin (complement factor D) and CAT increased most in their secretion from white adipocytes upon NE treatment with a 2.6-fold and 2.8-fold increase from basal state, respectively (Fig. 4). In addition, most of the known adipokines mentioned earlier like ectonucleotide pyrophosphatase/phosphodiesterase family

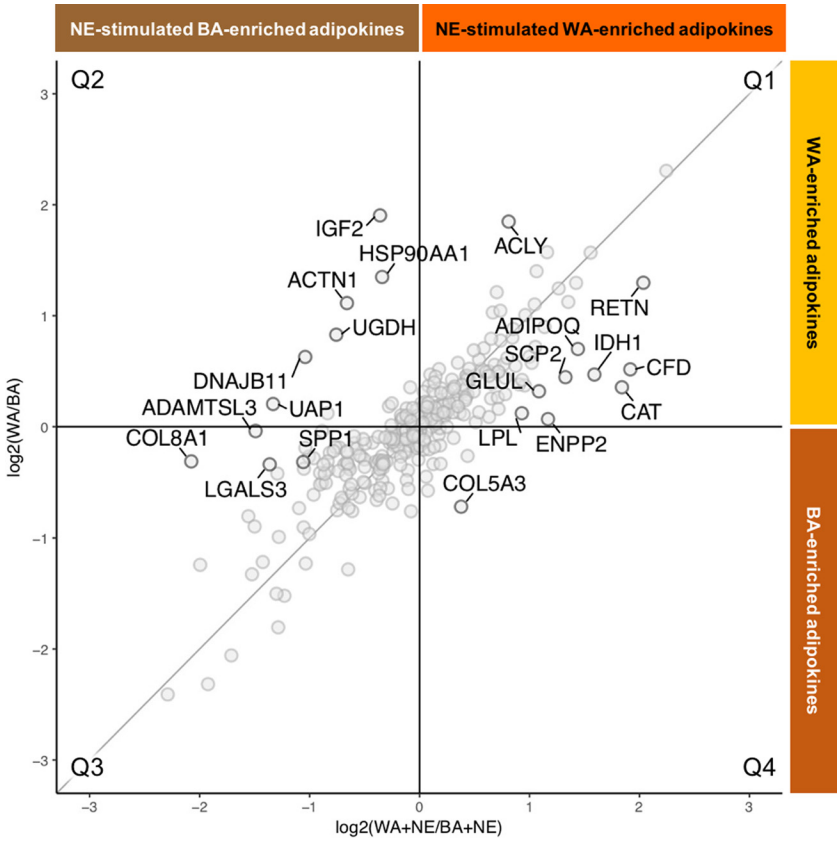

FIG. 4. **The secretory response of primary murine white and brown adipocytes between the NE-stimulated and basal state.** Scatterplot representing the fold changes of the significantly differentially secreted proteins from Figs. 2 and 3, *i.e.* between white and brown adipocytes in the basal state and upon NE-stimulation. Proteins in Q1 and Q2 represent white adipocyte-enriched adipokines in the unstimulated state (y axis > 0), while Q3 and Q4 display brown adipocyte-enriched adipokines in the basal state (y axis < 0). Proteins in Q1 and Q4 are more secreted from white than brown adipocytes upon NE (x axis > 0), while Q2 and Q3 represent proteins higher secreted from brown than white adipocytes upon NE (x axis < 0). Only proteins that were detected in both analyses are represented. Proteins with preferential NE-responsive secretion in brown or white adipocytes are labeled in black. WA: white adipocytes, BA: brown adipocytes, Q1–4: quadrant 1–4.

member 2, lipoprotein lipase, adiponectin, and resistin were increased in secretion from white adipocytes upon NE treatment.

Oppositely, in Q3, NE stimulation increased the secretion of collagen alpha-1(VIII) chain (COL8A1), galectin-3 (LGALS3) and osteopontin (SPP1) in brown adipocytes (Fig. 4). Glucose uptake via Glut4 is important for brown adipocytes, and LGAL3 was found to be crucial for Glut4-mediated glucose utilization in skeletal muscle and aortic endothelium (32). LGAL3 has also been shown to promote adipogenesis (33). Thus, NE-stimulated elevation of LGAL3 secretion from brown adipocytes could modulate adipogenesis and glucose uptake.

Furthermore, in Q2, Uridine-diphospho (UDP)-glucose 6-dehydrogenase showed a three-fold increase in secretion from white to brown adipocytes upon NE treatment. UDP-glucose 6-dehydrogenase is an extracellular matrix enzyme responsible for the synthesis of hyaluronan (HA) and is important for tissue organization, development, and cell proliferation (34). Given that hyaluronan is a major component of the adipose tissue ECM and affects adipogenesis and adipose tissue function (35), we speculate that UDP-glucose 6-dehydrogenase mediates these effects via hyaluronan in NE-treated brown adipocytes. On the other hand, IGF2, a fetal mitogen, showed a fivefold higher secretion in white adipocytes in the basal state (Fig. 2*A*), but this differential secretion was abolished with NE treatment. We cannot conclude whether IGF2 secretion from brown adipocytes increased or white adipocyte secretion decreased with NE treatment resulting in no differential secretion. As IGF2 causes a decrease in white and brown adipogenesis, we speculate that the latter scenario occurs in order to abolish this inhibitory effect on adipogenesis upon NE treatment (36, 37).

Interestingly, in Q4, collagen type V alpha 3 chain showed a secretion with twofold differential increase in white adipocytes. This collagen V chain is highly expressed in white adipocytes and is an important ECM component responsible for glucose homeostasis and adipose tissue expansion (38). Compared with Q2, only a few proteins in Q4 strongly changed their secretion ratios, thus we identified more relative changes in secretion favoring brown adipocytes upon NE stimulation.

In summary, by comparing the secretome of white and brown adipocytes in their basal and NE-stimulated state, we identified a number of secreted proteins responsive to NE treatment. These proteins are involved in various adipocyte processes like ECM organization, lipolysis, adipogenesis, glucose uptake, and protection against oxidative damage.

NE Stimulation of Primary Brown Adipocytes Broadly and Significantly Changes the Secretion of Batokines—The previously described analyses gave us an insight into the secretome differences between white and brown adipocytes, in the presence or absence of NE, but they do not reveal NE-induced changes in the brown adipocyte secretome itself.

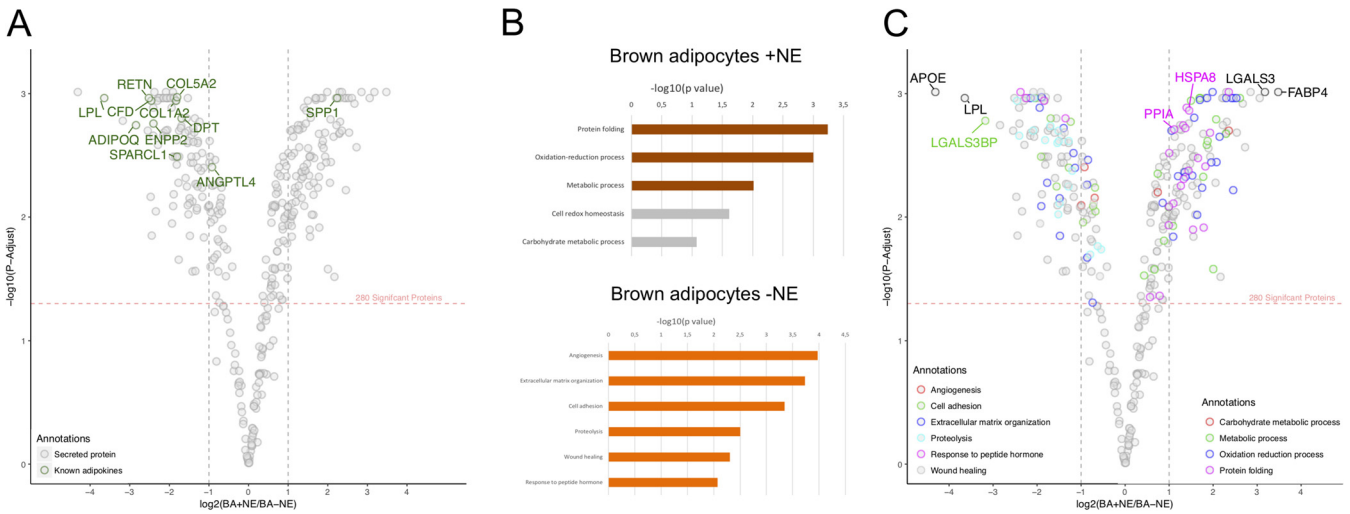

FIG. 5. **Comparative secretome analysis of primary murine brown adipocytes with and without NE.** *A*. Volcano plot depicting 280 significantly (p.adj $<$ 0.05, nominal p value cutoff = 0.023) differentially secreted proteins and 11 known adipokines (in green). *B*. GO enrichment analysis (p value threshold of 0.01) of the 280 proteins based on their higher secretion with or without NE. Significantly enriched GO terms are in color and non-significant ones in gray (p value threshold of 0.1). *C*. Volcano plot as in panel *A*. Proteins belonging to the enriched GO terms are colored, respectively. Additional top differentially secreted and discussed proteins are named in black. WA: white adipocytes, BA: brown adipocytes.

Therefore, we treated SVF-derived, differentiated brown adipocytes with NE for 24 h and compared their secretome to that of untreated brown adipocytes and obtained 280 significantly differentially secreted proteins (p-adj < 0.05, nominal p value cutoff = 0.039, Fig. 5*A*, supplemental Table 8).

Among these 280 proteins, the aforementioned known adipokines lipoprotein lipase, adipsin, ectonucleotide pyrophosphatase/phosphodiesterase family member 2, adiponectin, collagen alpha-2(I) chain, collagen alpha-2(V) chain, secreted protein, acidic, cysteine-rich (SPARC)-like protein 1, dermatopontin, and osteopontin showed enhanced secretion from brown adipocytes without NE stimulation (Fig. 5*A*). Moreover, we found that angiopoietin-like 4, an adipokine highly expressed in brown adipocytes (39), is also secreted. Interestingly, the secretion of angiopoietin-like 4 was repressed by NE treatment, which coincides with its decreased expression in brown adipocytes upon cold exposure (40).

GO enrichment analysis revealed "Protein folding" as the most significantly enriched term for the NE-induced proteins (Fig. 5*B*, supplemental Table 9). This GO term included heat shock protein 8 and peptidylprolyl isomerase A, which are integral components of chaperone-mediated autophagy preceding lipolysis (41) and adipogenesis (42), respectively (Fig. 5*C*). "Oxidation-reduction process" was the second most significantly enriched term upon NE treatment. Proteins belonging to this GO term comprised catalase, heme oxygenase 1, thioredoxin 1, and members of the peroxiredoxin family. These proteins and enzymes exhibit strong antioxidative properties, which could protect brown adipocytes against NE-triggered rise in reactive oxygen species production (43).

On the other hand, proteins with higher secretion without NE stimulation were enriched for GO terms associated with ECM organization and angiogenesis (Fig. 5*B*, *lower panel*, supplemental Table 10). Some of these include LGAL3 ("Cell adhesion"), SPARC-related modular calcium-binding protein 1 ("Extracellular matrix organization"), and plasminogen activator ("Angiogenesis"). Thus, in brown adipocytes NE-induced secreted proteins were involved in several important metabolic and oxidation-reduction processes, in particular antioxidative proteins, while the secretion of proteins associated with ECM organization and angiogenesis decreased (Fig. 5*C*). Interestingly, while we found ECM proteins to be higher secreted in brown than white adipocytes in the unstimulated state (chapter 1), the secretion of ECM proteins was diminished by NE.

Among the NE-induced proteins, fatty acid binding protein 4 (FABP4), a lipid transport protein crucial for BAT thermogenesis, exhibited the highest (10.5-fold) increase in secretion followed by LGAL3 (8.5-fold) (Fig. 5*C*). Studies have shown that FABP4 is required for uptake of nonesterified fatty acids and storage of triglycerides in BAT. Accordingly, FABP4 and FABP5 double knockout mice exhibit impaired thermogenesis due to depletion of BAT energy stores (44). Interestingly, the secretion of FABP5 was also increased fourfold upon NE treatment in our analysis.

Among the NE-repressed proteins, we identified apolipoprotein E and lipoprotein lipase, both involved in the uptake and lipolysis of chylomicrons and very low density lipoproteins, as proteins with the strongest decrease (20-fold and 12-fold, respectively) in secretion (Fig. 5*C*). However, the resultant physiological consequence of this reduced secretion is unclear since BAT mainly replenishes its intracellular triglyceride stocks via lipolysis mediated uptake of lipoprotein-derived fatty acids (45, 46). Interestingly, we also found LGAL3 bind-

ing protein (LGALS3BP), a binding partner of LGAL3, to be significantly reduced in secretion upon NE treatment, as opposed to LGAL3 whose secretion increased. LGALS3BP and GAL-3 are under different transcriptional regulation and together mediate cell-cell adhesion (47). A recent study described a secondary function of LGALS3BP in affecting Wnt signaling by binding Wnt ligands and improving their storage, spread, and bioavailability (48). As Wnt proteins block brown adipogenesis, it may be speculated that NE contributes to reduced secretion of LGALS3BP to indirectly reduce intracellular Wnt signaling in brown adipocytes (49).

DISCUSSION

There are a number of studies on the secretome of white adipocytes, in mice and humans (50–53). However, a comparative proteomic analysis of secreted factors from white and brown adipocytes has not been reported yet, despite the fact that BAT, like its white counterpart, also exhibits an endocrine function by secreting adipokines, called batokines or brown adipokines. Herein, we have studied the secretome of murine SVF-derived primary white and brown adipocytes by using mass spectrometry combined with AHA labeling and pulsed SILAC with the aim of characterizing the white and brown adipocyte secretome and identifying potential novel adipokine candidates. We developed this approach to analyze the secretome of primary hepatocytes and Hepa 1–6 cells, lipopolysaccharide (LPS)-stimulated macrophages, and human prostate cancer cell line (PC3) and human prostate stromal myofibroblast cell line (WPMY-1) cells under serum starvation (12). The use of click-chemistry offers two main advantages in the study of the adipocyte secretome. Firstly, the primary adipocytes could be cultured in media containing serum, which prevents changes in growth conditions and in the native secretome. Most secretome approaches have to avoid the use of serum to reduce contamination and facilitate detection of genuine secretory proteins. With our methodology, the substitution of methionine with AHA in the cellular proteome enables the selective enrichment of secreted proteins from the supernatant thereby reducing contamination by serum proteins. Secondly, AHA labeling circumvents extensive time-consuming peptide fractionation owing to the selective enrichment and thus reduced sample complexity, which expedites the whole secretome analysis. The reliability of this technique was evident in the high correlation between the replicates in each analysis (Fig. S1) and the detection of several well-known adipokines.

A confounding factor in classical secretome analysis is the inability to distinguish genuine secretory proteins from those that originate from lysed cells. An added advantage of our methodology is that it is far less sensitive to this phenomenon. Specifically, our approach relies on the detection of newly synthesized proteins that have incorporated AHA and SILAC amino acids during the experiment. By definition, this can only occur in intact living cells. If broken cells are present at all (which cannot be excluded), their (unlabeled) proteins will be removed during the AHA-enrichment, along with serum proteins that are present in high abundance but that similarly lack AHA. In the worst case, if cells break during cell incubation, it is reasonable to expect that this occurs to the same degree between compared conditions (*e.g.* ± NE). Such cases would be disregarded in our data since we were primarily interested in proteins that are differentially secreted, *i.e.* that derive from secretory activity and not from cell damage. In line with this, we could not observe any prominent visual indicators of cell death during the incubation of adipocytes with AHA-supplemented SILAC media. To obtain a quantitative estimate, we measured the percentage of cell death by measuring LDH release in AHA-supplemented growth media in a pilot study and found that there is about 20% cell death among the adipocytes with no increase after 24 h (Fig. S2*A*). As this is the same media used in the secretome analysis, it can be concluded that after the first 24 h there is no significant rise in cell death.

Other studies have focused on the white adipocyte secretome in various settings like adipogenesis (54), insulin resistance (55) and depot-specific differences (56). However, no one so far has investigated the secretome response induced by NE, a catecholamine that mediates essential physiological responses. Here we provide the first systematic study investigating the brown adipocyte secretome—in addition to the white adipocyte secretome—and their response to NE. We accomplished this by conducting three comparative analyses: the first two compared the secretome of white and brown adipocytes without and with NE treatment, respectively (Figs. 2 and 3), while the third experiment compared brown adipocytes with and without NE stimulation (Fig. 5). Our study revealed that i) in the absence of NE carbohydrate metabolism-regulating proteins are favored in the white adipocyte secretome, while no specific protein class is predominant in the brown adipocyte secretome (Fig. 2*B*), ii) in white adipocytes NE triggers increased secretion of several well-known adipokines, while it promotes secretion of novel adipokines in brown adipocytes (Fig. 3*C*), iii) the secretory response between NE-stimulated and basal state is diverse ranging from glucose and lipid metabolism to adipogenesis and resistance to oxidative stress (Fig. 4), and iv) the brown adipocyte secretome is substantially altered upon NE treatment (Fig. 5*C*).

As expected, proteins involved in carbohydrate metabolism were enriched in white adipocytes without NE treatment when compared with brown adipocytes (Fig. 2*B*). However, finding an enrichment for tricarboxylic acid proteins in white adipocytes upon treatment with NE was unexpected as the TCA takes place in the inner mitochondrial membrane, and most of the proteins were annotated as mitochondrial proteins. The analysis in brown adipocytes with and without NE revealed that the majority of brown adipokines with NE-increased secretion are involved in redox reactions like peroxiredoxin-4,

catalase, and heme oxygenase 1 (Fig. 5*B*). An often made association with reactive oxygen species production and oxidative stress in brown adipocytes has been UCP1 activation and mitochondrial uncoupling. While Shabalina and colleagues have shown that UCP1 is not involved in control of reactive oxygen species production in brown-fat mitochondria (57), several studies have shown that UCP1 plays an important and evolutionary conserved function in the reduction of superoxide production (58–60). Stier and colleagues also demonstrated that cold exposure activated UCP1 in BAT allowed wild-type mice to increase their metabolism to generate heat while preventing damage by oxidative stress (61). Interestingly, we observed a distinct secretory profile between white and brown adipocytes, and our findings suggest that brown adipocyte secreted factors may indeed contribute to prevent NE-induced oxidative stress along with activated UCP1. Moreover, in our comparison of the white and brown adipocyte secretome in the NE-stimulated and unstimulated state, we observed that NE increased the differential secretion of most classical adipokines like adiponectin, adipsin, and resistin in white adipocytes while novel adipokines like osteopontin and LGAL3 were more highly secreted in brown adipocytes (Fig. 4). This observation underscores our findings that i) most well-known adipokines are in fact NE-responsive white adipocyte-enriched secreted proteins and ii) the majority of the NE-responsive brown adipocyte-enriched secreted proteins are novel uncharacterized adipokines, a treasure trove of metabolic regulators that await further functional characterization.

As outlined above, we detected several well-known adipokines like adipsin, adiponectin, and resistin in our analyses (supplemental Table 2), but not others such as tumor necrosis factor α, interleukin-6, and leptin, similar to Adachi, Kumar *et al.* (62). However, their lack of detection does not necessarily mean their lack of secretion. This is especially true for leptin that was absent in several other secretome screens (63) and was only detectable using antibody-based methods (64, 65) leading to the speculation that leptin's structural properties reduce its detectability by mass spectrometric analysis. Indeed, we were also able to detect leptin (and resistin) using the MILLIPLEX® MAP Mouse Metabolic Hormone panel on the Luminex xMAP® platform (MAGPIX®) from both white and brown adipocytes after 6 and 24 h of incubation with fresh growth media (Fig. S2*B*). The detection of resistin secretion in white and brown adipocytes by this method nicely recapitulated the secretion ratio determined in our secretome analysis.

Moreover, even for the well-known classical adipokines like adiponectin and resistin, we uncovered valuable novel insight into their secretion profile from white and brown adipocytes. The secretion of adiponectin was not drastically different in the basal state among white and brown adipocytes (Fig. 2), but was higher upon NE from white compared with brown adipocytes (Fig. 3), partly because of reduced secretion from brown adipocytes by sevenfold upon NE treatment (Fig. 5). As adiponectin suppresses thermogenesis by inhibiting UCP1 expression, its decreased secretion in brown adipocytes could prevent the autocrine inhibition of thermogenesis (66). For resistin the secreted levels were higher from white than brown adipocytes and this difference was further increased upon NE stimulation. Similar to adiponectin, NE-mediated decrease in secretion of resistin from brown adipocytes diminishes its negative autocrine effects on BAT activity and adipogenesis (67).

In terms of novel batokine candidates, LGAL3 and osteopontin are two interesting proteins that were detected in our study. LGAL3 is a member of the lectin family known to be protective in obesity (68) and inflammation (69). In our analyses, its secretion was not different in the absence of NE but was 2.5-fold higher upon NE stimulation in brown compared with white adipocytes (explained by an eightfold increase upon NE treatment in brown adipocytes). The aforementioned decrease in adiponectin secretion fits with the increase in LGAL3 secretion as adiponectin represses the secretion of LGAL3 from adipocytes (70). These observations point to an important role of LGAL3 in propagating beneficial effects of NE-stimulated BAT activity possibly by regulating inflammation and/or promoting thermogenesis. In addition, we found osteopontin secretion to be responsive to NE treatment, with a fourfold increase in brown adipocytes (Fig. 5) leading to twofold stronger increase in brown compared with white adipocytes (Fig. 3). Osteopontin is an extracellular matrix protein involved in biomineralization, tissue remodeling, and inflammation (71). It is primarily associated with bone metabolism and remodeling but has also been associated with obesity and insulin resistance (72, 73) and is a putative link between bone homeostasis and adipose tissue (74). We speculate that osteopontin released by activated BAT may be responsible for the positive correlation observed between bone anabolism/remodeling and BAT volume (75).

In summary, we obtained novel secretion profiles of known adipokines and novel adipokine candidates from brown and white adipocytes, and provide a large resource of significantly differentially secreted proteins: 141 between white and brown adipocytes (Fig. 2), 186 between white and brown adipocytes upon NE treatment (Fig. 3), and 280 responsive to NE from brown adipocytes, with most of them being novel adipokines (Fig. 5). Furthermore, we not only present novel secretory profiles for individual proteins but also functionally enriched protein classes that were significantly changed between white and brown adipocytes and were responsive to NE stimulation. To conclude, with our study, we provide a comprehensive catalogue of novel adipokine candidates secreted from white and brown adipocytes and responsive to NE, which may serve as basis for numerous hypothesis-driven functional studies in the near future for characterizing adipocyte-secreted proteins. Given the beneficial effects of BAT activation on systemic metabolism and its endocrine function, this study

provides an archive of potential brown adipokines and biomarkers for activated BAT.

DATA AVAILABILITY

The mass spectrometry proteomics data have been deposited to the ProteomeXchange Consortium (http://proteomecentral.proteomexchange.org) via the PRIDE (16) partner repository with the dataset identifier PXD009280. Annotated MS/MS spectra can be viewed through MS-Viewer (http://msviewer.ucsf.edu/prospector/cgi-bin/msform.cgi?form=msviewer) with the search key 2rncktsta6.

* This work was funded by the EU-FP7 Collaborative Project DIABAT (HEALTH-F2–2011-278373; www.diabat.org) and the Helmholtz Alliance ICEMED (HA-314; http://icemed.helmholtz.de).

S This article contains supplemental material Supplemental Table 1–3 and 5–10 and Figs. S1 and S2.

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