

Vesicular storage, vesicle trafficking, and secretion of leptin and resistin: the similarities, differences, and interplays

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Abstract

Adipose tissue is a highly active endocrine organ secreting a variety of signaling molecules called adipokines. Leptin and resistin are two adipokines critically involved in metabolic homeostasis. Nevertheless, the secretory pathways of these adipokines and their interplays are poorly elucidated. In this work, we have comparatively studied several key aspects of leptin and resistin secretion from 3T3-L1 adipocytes. It was found that leptin and resistin molecules are

compartmentalized into different secretory vesicles. The trafficking of leptin and resistin vesicles, and the secretion of leptin and resistin are oppositely regulated by insulin/glycolytic substrates and cAMP/protein kinase A. Interestingly, these two adipokines adversely influence each other on secretion and vesicle trafficking. Finally, we demonstrated that both leptin and resistin secretion are Ca^{2+} dependent.

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Introduction

Adipose tissue, which was previously regarded as a passive depot of excess energy (fat), has recently been recognized as the largest and a highly active endocrine organ secreting a spectrum of signaling molecules called adipokines (including leptin, resistin, adiponectin, visfatin, tumour necrosis factor- α , etc). These adipokines play key roles in regulating energy homeostasis, lipid metabolism, immunity, and other physiological functions (Rosen & Spiegelman 2006, Trujillo & Scherer 2006, Lago *et al.* 2007, 2009). Among them, leptin and resistin have attracted much interest because of their critical involvement in metabolic disorders (Rondinone 2006, Rosen & Spiegelman 2006).

There are evidences that the functions of leptin and resistin as well as their secretion are intimately linked. For instance, the secretion of leptin and resistin is similarly controlled by diet. Fasting reduces the serum levels of both adipokines, while food intake does the opposite (Kolaczynski *et al.* 1996, Rajala *et al.* 2004). Both adipokines inhibit differentiation of adipocytes and thus development of adipose tissue (Zhou *et al.* 1999, Kim *et al.* 2001, Dal Rhee *et al.* 2008). They all encourage angiogenesis and actively regulate immune responses (Bouloumie *et al.* 1998, Reilly *et al.* 2005, Mu *et al.* 2006, Lago *et al.* 2007, Anagnostoulis *et al.* 2008). On the other hand, they antagonize each other in some cases (Rondinone 2006). For instances, leptin increases insulin sensitivity, whereas resistin suppresses it (Ogawa *et al.* 1999, Steppan *et al.* 2001); leptin reduces gluconeogenesis, whereas resistin promotes it (Rossetti *et al.* 1997, Banerjee *et al.* 2004); leptin enhances

AMPK-mediated signal transduction, while resistin decreases it (Minokoshi *et al.* 2002, Palanivel & Sweeney 2005).

The mechanisms of leptin and resistin secretion, and the crosstalks between them, however, are poorly elucidated. Based on confocal fluorescence microscopy, total internal reflection fluorescence microscopy (TIRFM), and immunoblotting, we aim to study the compartmentalization and the regulations of vesicular trafficking and secretion of both leptin and resistin, using adipocytes differentiated from 3T3-L1 fibroblasts. The similarities, differences, and interplays between these two important adipokines are revealed.

Materials and Methods

Cell culture and differentiation

Murine 3T3-L1 fibroblasts (American Type Culture Collection, Rockville, MD, USA) were cultured in DMEM (Gibco) supplemented with 10% heat-inactivated bovine calf serum (Gibco) and 1% penicillin–streptomycin (Gibco) at 37 °C in a humidified atmosphere of 5% CO_2 /95% air. Differentiation of 3T3-L1 fibroblasts to adipocytes was induced similarly as described previously (Shao & Lazar 1997). Specifically, after cells reached confluence for 2 days (referred as day 0), they were cultured in the differentiation medium for 2 days, which is DMEM supplemented with 10% fetal bovine serum (FBS), 1 μM dexamethasone, 10 $\mu\text{g}/\text{ml}$ insulin, and 0.5 mM isobutyl-1-methylxanthine. The cells were then maintained in the medium containing 10% FBS and 10 $\mu\text{g}/\text{ml}$ insulin for

2 days, and replenished with the DMEM containing 10% FBS. Differentiation was monitored by the visual appearance of fat droplets in the cells and oil red stain.

Plasmids

The plasmid encoding murine resistin was purchased from OriGene Technologies (Rockville, MD, USA). The plasmid encoding murine leptin was a kind gift from Prof. Jan Tavernier (Ghent University, Belgium). The Glut4-GFP plasmid was a kind gift from Prof. Jeffrey E Pessin (Albert Einstein College of Medicine, USA), and the Rab5-GFP plasmid was generously provided by Dr Sean Liour (Institute of Bioengineering and Nanotechnology, Singapore). The vector pEGFP-N1 was purchased from Clontech. The resistin/leptin-EGFP plasmids were constructed by subcloning the corresponding cDNAs into the vector pEGFP-N1 at the sites of Nhe I and AgeI. Insertion of cDNAs was verified by DNA sequencing. Differentiated 3T3-L1 cells grown on polylysine-coated glass coverslips (on day 7 or 8) were transfected with relevant plasmids (1–2 µg) using FuGENE6 Transfection Reagent (Roche), 3–4 days before the confocal or TIRFM imaging experiments.

Confocal microscopy

The 3T3-L1 adipocytes were fixed with 4% formaldehyde, permeabilized with 0.1% Triton X-100, blocked with 1.5% BSA before immunostaining and imaging. In some experiments, the adipocytes were transfected with plasmids encoding Glut4-GFP or Rab5-GFP, 3–4 days before fixation. Leptin molecules were immunostained first with chicken anti-leptin IgY antibody (Abcam, Cambridge, MA, USA) or rabbit anti-leptin IgG antibody (Sigma-Aldrich) and subsequently with the anti-IgY secondary antibody conjugated with FITC (Abcam) or anti-IgG secondary antibody conjugated with Atto 647 NHS (Sigma-Aldrich). Resistin molecules were immunostained first with rabbit anti-resistin IgG antibody (Biovision, Mountain View, CA, USA) and subsequently with the anti-IgG secondary antibody conjugated with Atto 647 NHS (Sigma-Aldrich). Confocal images were taken by a LSM 510 Meta confocal laser scanning microscope (Carl Zeiss, Göttingen, Germany).

TIRFM imaging and analysis

TIRFM was carried out at 25 °C using a Zeiss Axiovert 200 inverted microscope system (Carl Zeiss) equipped with a 100× 1.45 NA TIRF objective. EGFP was excited by a 488 nm laser, and the emission wavelength was collected at 520 nm. The laser beam was incident on the coverslip (refractive index ~1.52) at 68–70 °C from the normal. The penetration depth of the evanescent field is calculated to be ~100 nm. Using MetaMorph 6.3 program (Molecular Devices, Sunnyvale, CA, USA), time-lapse TIRFM images were acquired by a CCD camera for 2 min with exposure time of 20 ms and sampling frequency of 2 Hz. Vesicles were

individually tracked using Image J (<http://rsb.info.nih.gov/ij/>). The vesicle velocity, dwell time, and arrival rate were analyzed by a program developed in Igor (WaveMetrics, Lake Oswego, OR, USA). Imaging was taken ~30 min after applying particular chemicals.

Western blot

Western blots under different conditions were conducted in parallel (same time and the same batch of cell subcultures), and cells were grown confluent in the flasks of same size. Therefore, the cell number for each experiment is similar. On day 9 of differentiation, 3T3-L1 adipocytes were incubated in serum-free medium (Lonza, Basel, Switzerland) for 2 h followed by medium collection (12 ml) and replenishment with the culture medium. The total amount of secreted protein in the collected medium was then quantified by a protein assay kit (Bio-Rad) based on the method of Bradford. This was used to calibrate the sample volume for the following immunoblotting experiments to minimize the influence due to the variation in cell number. In addition, intracellular GAPDH as an indicator of the total cell number was quantified in some experiments. Both measurements of total secreted proteins and intracellular GAPDH on the same batch of cell subcultures only exhibited insignificant differences. On day 10 or 11 of differentiation, the cells in 75 cm² flask were washed with PBS for three times and incubated in 12 ml serum-free medium containing 5.5 mM without (control) or with addition of 1) GPI (pyruvate, 1 mM; glucose, 25 mM as final concentration; and insulin, 100 ng/ml) or 2) GPI and 10 µM forskolin or 3) 10 µM forskolin or 4) 0.1 µM leptin or 5) 0.1 µM resistin. In some experiments, the cells were pre-incubated with intracellular calcium chelator BAPTA-AM (50 µM) in the calcium-free bath solution for 15 min to deplete intracellular Ca²⁺. In some experiments, 10 mM EGTA was added in the serum-free medium to deplete extracellular Ca²⁺. After 2 h, the medium was harvested and concentrated by centrifugal filter devices (Amicon Ultra, Millipore, Billerica, MA, USA) for western blot analysis. Samples were separated on SDS-PAGE. Proteins were then transferred onto polyvinylidene fluoride (PVDF) membranes (Bio-Rad) followed by blocking for 2 h at 4 °C with 5% non-fat dry milk in TBST buffer (10 mM Tris, 150 mM NaCl, and 0.05% Tween-20, pH 7.5). The PVDF membrane was subsequently incubated with the primary rabbit anti-leptin (Sigma-Aldrich) or goat anti-resistin (Santa Cruz Biotechnology, Santa Cruz, CA, USA) or anti-EGFP antibodies (Biovision) in TBST buffer at room temperature for 12 h. After washing three times with TBST buffer, the membrane was incubated with a secondary antibody conjugated HRP (Thermo Scientific, Rockford, IL, USA) for 6 h at room temperature. The reactions were visualized with CN/DAB detection kit (Thermo Scientific). PVDF membranes were then scanned using Bio-Rad's Densitometer and analyzed using Bio-Rad's QualityOne software. Different rabbit anti-leptin (Santa Cruz), goat anti-resistin (Abcam), and rabbit anti-resistin (Biovision) antibodies were also tested, and they gave similar results.

$[Ca^{2+}]_i$ imaging

The 3T3-L1 adipocytes were loaded with 5 μ M fura2 acetoxyethyl ester (Fura2-AM, Molecular Probes, Eugene, OR, USA) for 60 min in culture medium. Then the cells were rinsed and placed in the bath solution for more than 30 min before the experiment to allow retention of the dye after hydrolysis of the ester. Fluorescent signals in response to GPI, forskolin, calcimycin, or high K^+ stimulation were recorded from single cells using a photometry system (TILL Photonics GmbH, Gräfelfing, Germany). The intracellular calcium concentration ($[Ca^{2+}]_i$) was reported as the ratio of Fura2 fluorescence intensity resulting from the two excitation wavelengths at 340 and 380 nm respectively (F340/F380).

Solutions

The bath solution used in confocal, TIRFM, and Ca^{2+} imaging experiments contained (in mM, titrated to pH 7.4): 150 NaCl, 5.4 KCl, 2 $MgCl_2$, 2 $CaCl_2$, 5 glucose, and 10 HEPES. Two millimolar $CaCl_2$ were omitted in the Ca^{2+} -free bath solution, which was used to load BAPTA-AM in the immunoblotting experiments. In Ca^{2+} imaging experiments, high K^+ solution contains (in mM, titrated to pH 7.4): 40 NaCl, 105 KCl, 1 $MgCl_2$, 6 $CaCl_2$, 5 glucose, and 10 HEPES. In some experiments, GPI or 10 μ M forskolin or 0.1 μ M leptin or 0.1 μ M resistin or 1 mg/ml calcimycin was added in the bath solution.

Statistical analysis

Statistical data are expressed as mean \pm S.E.M. Because the vesicle dwell time and velocity give skewed distributions, their statistical significances were evaluated by the Mann-Whitney rank sum test (Bai *et al.* 2007, Zhou *et al.* 2007). All other values were evaluated by Student's unpaired *t*-test. $P < 0.05$ was considered to be statistically significant.

Results

Compartmentalization of leptin and resistin

We studied the compartmentalization of both leptin and resistin molecules using 3T3-L1-derived adipocytes. Based on immunostaining with adipokine-specific antibodies, confocal fluorescence microscopy revealed that both leptin and resistin molecules were segregated into numerous small vesicles throughout the cytosol, and that leptin and resistin vesicles were not colocalized (Fig. 1A). Confocal colocalization studies were then performed on 3T3-L1 adipocytes overexpressed with GFP-tagged Rab5 which is a molecular marker of early endosomes. As demonstrated in Fig. 1B and C, neither leptin nor resistin molecules were accumulated in early endosomes. Glut4 (listed as Slc2a4 in the MGI Database) is the glucose transporter responsible for insulin-regulated glucose disposal

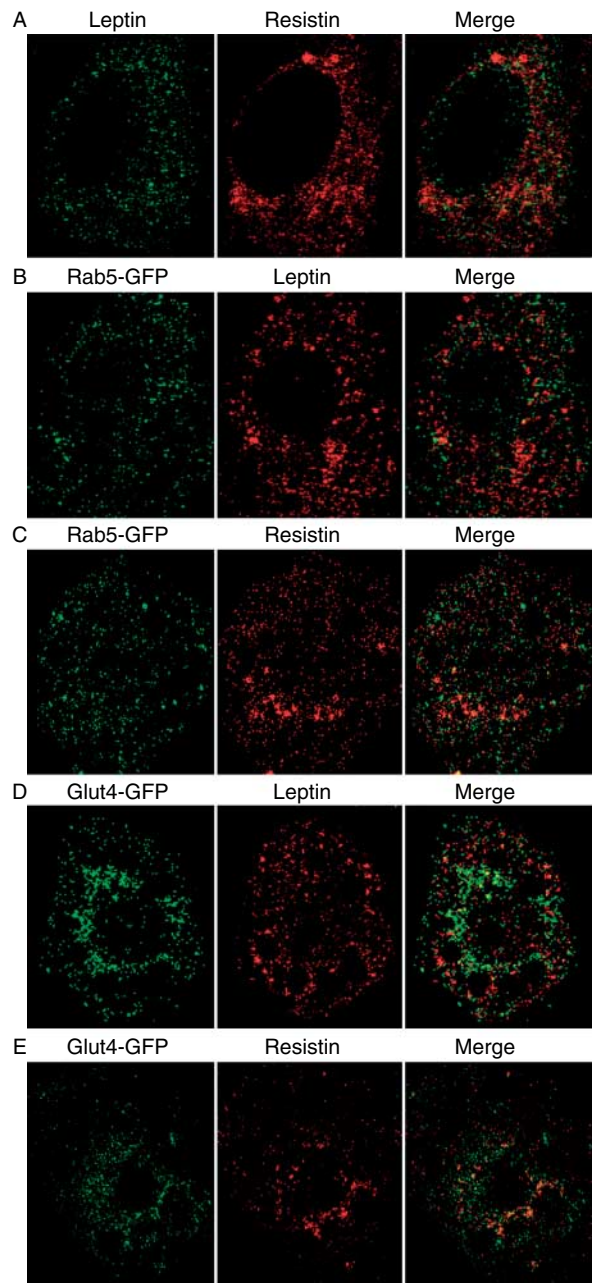


Figure 1 Compartmentalization of leptin and resistin molecules in 3T3-L1 adipocytes revealed by confocal imaging. (A) Distribution of immunostained leptin (left, FITC-conjugated secondary antibody) and resistin (middle, Atto 647 secondary antibody) molecules, and their colocalization (right, merge of left and middle). (B) Distribution of overexpressed Rab5-GFP (left) and immunostained leptin (middle, Atto 647 secondary antibody), and their colocalization (right). (C) Distribution of overexpressed Rab5-GFP (left) and immunostained resistin (middle, Atto 647 secondary antibody), and their colocalization (right). (D) Distribution of overexpressed Glut4-GFP (left) and immunostained leptin (middle, Atto 647 secondary antibody), and their colocalization (right). (E) Distribution of overexpressed Glut4-GFP (left) and immunostained resistin (middle, Atto 647 secondary antibody), and their colocalization (right).

in adipose tissue. Based on confocal imaging on adipocytes overexpressed with GFP-tagged Glut4, it was found that both leptin and resistin were not carried in insulin-sensitive Glut4-containing vesicles (Fig. 1D and E). Plentiful vesicular storage makes it possible for acute release of these adipokines upon triggering, suggesting existence of the regulated secretory pathways. The distinct identities of leptin and resistin vesicles imply differences between the secretory routes of these adipokines.

Trafficking of leptin and resistin vesicles is differentially regulated

TIRFM, which selectively and evanescently illuminates the thin region (<200 nm) just above the interface between the glass coverslip and the adhered cell, is instrumental to provide insights on phenomena occurring at or near the plasma membrane. It complements the electrophysiological methods for study of exocytosis (Chen & Gillis 2000, Xue *et al.* 2009a). It has been revealed by TIRFM that secretory vesicles, such as large dense core secretory vesicles (LDCVs) in neuroendocrine cells and synaptic vesicles (SVs) in neurons, undergo constant trafficking in the subplasmalemmal region (Holz & Axelrod 2008). They move laterally while dwelling in the subplasmalemmal region. Such lateral movement can be characterized as random Brownian motion confined within a limited range by certain physical barrier or tethering forces (Zhang *et al.* 2008). Meanwhile, vesicles travel vertically, i.e. they arrive from the inner cytosol to the subplasmalemmal region and retrieve back after some time. The mobility and trafficking dynamics of secretory vesicles directly relate to their fusion competence and their secretion kinetics (Degtyar *et al.* 2007, Holz & Axelrod 2008, Zhang *et al.* 2008, Xue *et al.* 2009b).

Subplasmalemmal leptin vesicles (Fig. 2A) and resistin vesicles (Fig. 2B) in live 3T3-L1 adipocytes were lightened by overexpressing EGFP-tagged leptin or resistin molecules and were individually resolved under TIRFM. Just like other secretory vesicles, these adipokine-containing vesicles undertake constant lateral and vertical trafficking. The movement of individual vesicles was tracked at 0.5 s time interval for 2 min to obtain information about the velocity of lateral movement and the dwell time of vesicles which emerged and then disappeared during imaging. Typical trajectories of lateral motion of a leptin vesicle (top) and a resistin vesicle are depicted in Fig. 2.

It has been shown that the cocktail of insulin and high concentration of glycolytic substrates (glucose and pyruvate; abbreviated as GPI) can synergistically and potently stimulate leptin secretion (Levy & Stevens 2001), possibly through triggered vesicular exocytosis (Roh *et al.* 2000). GPI stimulation mimics the hyperinsulinemic-hyperglycemic conditions associated with type 2 diabetes. Interestingly, it is evident from Fig. 3A (top) that GPI significantly increased the velocity of leptin vesicles (ten GPI-treated cells: 411.7 ± 12.2 nm/s versus nine control cells: 239.4 ± 7.4 nm/s, $P < 0.001$). The competence of vesicle fusion requires sufficient vesicle mobility (Degtyar *et al.* 2007,

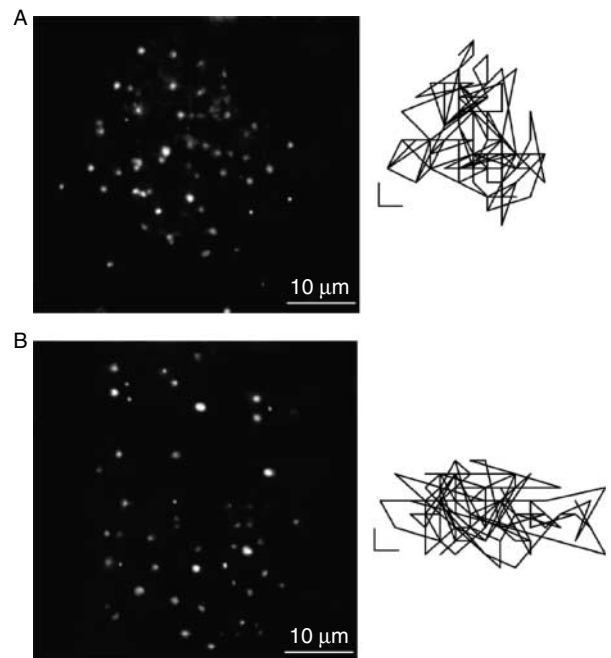


Figure 2 Typical TIRFM images of 3T3-L1 adipocyte overexpressed with leptin-EGFP (A) or resistin-EGFP (B). Individual leptin- or resistin-containing vesicles can be resolved as green dots. Typical motion trajectories of a subplasmalemmal leptin (A) and resistin (B) vesicles are depicted on the right. The scale bars = 200 nm.

Zhang *et al.* 2008). It is, therefore, not surprising that GPI stimulates not only leptin secretion but also its vesicle trafficking. Consistently, the rate of vesicle arrival (vertical transport) was also enhanced by GPI (total of 50.5 ± 4.5 vesicles arrived in 2 min versus 22.9 ± 1.6 vesicles, $P < 0.001$; Fig. 3A, middle). But it is worth noting that the total number of visible vesicles in the subplasmalemmal region remained stable, meaning that the increased vesicle arrival was balanced by vesicle release and/or increased vesicle retrieval. On the other hand, the dwell time of the vesicles in the subplasmalemmal region was largely reduced by GPI (19.3 ± 0.8 vs 23.1 ± 0.9 s, $P < 0.05$) (Fig. 3A, bottom), presumably because of enhanced vertical trafficking. This may also be due in part to that, under stimulation, vesicles were released shortly after arriving in the subplasmalemmal region.

In contrast to leptin vesicles, the lateral and vertical trafficking of resistin vesicles was largely reduced by GPI (Fig. 3B, top and middle), implying the inhibitory effect of GPI on vesicular release of resistin. Specifically, the velocity and arrival rate of resistin vesicles in nine GPI-treated cells were significantly reduced compared with nine control cells (78.1 ± 3.0 vs 197.5 ± 8.7 nm/s, $P < 0.001$; and 21.1 ± 2.8 vesicles arrived in 2 min versus 29.7 ± 1.5 vesicles, $P < 0.05$), and the dwell time of resistin vesicles was elongated by GPI treatment (25.1 ± 0.8 vs 29.3 ± 0.7 s, $P < 0.05$). Clearly, GPI differentially modulates the trafficking, thus likely secretion, of leptin and resistin vesicles.

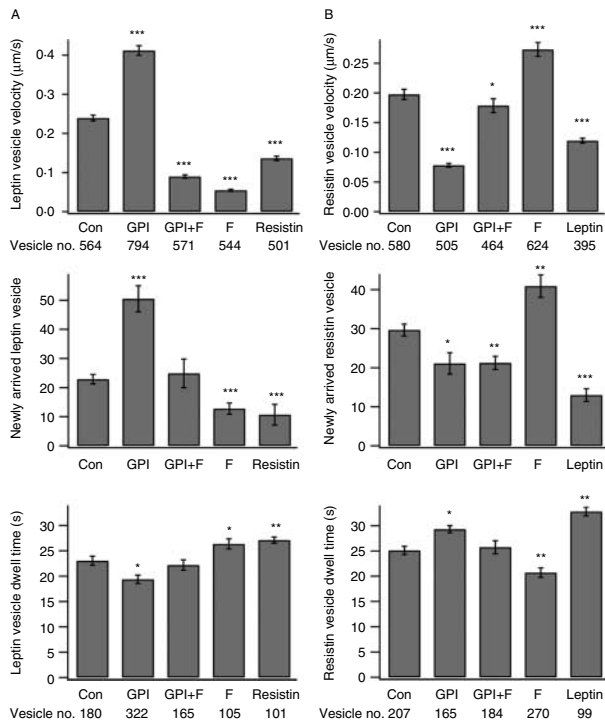


Figure 3 Trafficking of leptin (A) and resistin (B) vesicles. Fluorescently labeled vesicles were individually tracked under TIRFM at 0.5 s time interval for 2 min. The statistics (mean \pm S.E.M.) of vesicle velocity (top), the number of vesicles arrived from inner cytosol (middle), the vesicle dwell time (bottom) was obtained in 3–4 independent experiments from nine untreated leptin-expressing cells (Con), ten GPI-treated leptin-expressing cells (GPI), nine GPI- and forskolin-treated leptin-expressing cells (GPI+F), nine forskolin-treated leptin-expressing cells (F), nine resistin-treated leptin-expressing cells, nine untreated resistin-expressing cells (Con), nine GPI-treated resistin-expressing cells (GPI), nine GPI- and forskolin-treated resistin-expressing cells (GPI+F), nine forskolin-treated resistin-expressing cells (F), eight leptin-treated resistin-expressing cells. The number of vesicles analyzed for each condition is as indicated. * $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$ were determined by Student's *t*-test (for normally distributed arrived vesicle number), or Mann-Whitney test (for skewedly distributed vesicle velocity and dwell time).

Previous experiments have demonstrated that forskolin, which activates protein kinase A (PKA) by increasing the level of cAMP, inhibits insulin-stimulated leptin production from primary adipocytes (Alonso-Vale *et al.* 2005). Consistently, we found that forskolin inhibited both the lateral and vertical trafficking of leptin vesicles, and increased the vesicle dwell time (Fig. 3A). In addition, forskolin completely blocked the facilitating effects of GPI, suggesting that cAMP/PKA may act downstream of GPI (Fig. 3A). Conversely, forskolin significantly enhanced the lateral and vertical trafficking of resistin vesicles, and reduced the vesicle dwell time (Fig. 3B). In addition, forskolin counteracted GPI inhibition on vesicle velocity and elongation on dwell time (Fig. 3B). Taken together, our experiments showed that GPI and forskolin

differentially regulate the trafficking (thus, likely exocytosis) of leptin and resistin vesicles.

Interestingly, leptin and resistin antagonize each other on vesicle trafficking. Compared with the control, applying resistin to the bath solution significantly slowed the lateral motion of leptin vesicles (nine cells: 136.3 ± 5.6 nm/s, $P < 0.001$ versus control) and the rate of vesicle delivery (10.7 ± 3.6 vesicles arrived in 2 min, $P < 0.01$ versus control), and increased the vesicle dwell time (27.1 ± 0.6 s, $P < 0.01$ versus control) (Fig. 3A). On the other hand, application of leptin to the bath solution significantly slowed the lateral motion of resistin vesicles (eight cells: 119.5 ± 4.3 nm/s, $P < 0.001$ versus control) and the rate of vesicle delivery (13 ± 1.6 vesicles arrived in 2 min, $P < 0.001$ versus control), and increased the vesicle dwell time (32.8 ± 0.8 s, $P < 0.01$ versus control) (Fig. 3B). Therefore, it may be speculated that leptin and resistin inhibit the vesicular exocytosis of each other. Such interplay between leptin and resistin postulates the existence of autocrine regulation of adipokine secretion from adipocytes.

We occasionally observed full fusion of leptin-EGFP vesicles under GPI stimulation (Fig. 4A) and full fusion of resistin-EGFP vesicles under forskolin stimulation (Fig. 4B). As reported previously (Bai *et al.* 2007), the fusion events can be characterized by 1) abrupt increase of fluorescence intensity about the vesicle center due to rapid release of fluorescent molecules, 2) accompanying increase of fluorescent intensity in the peripheral region due to diffusion of released molecules, and 3) final disappearance of the vesicle. Thus, leptin-EGFP and resistin-EGFP are packed into fusion-competent vesicles. The secretion of leptin-EGFP and resistin-EGFP, without or with stimulation (GPI or forskolin), was also confirmed using western blot based on the antibody against EGFP. Secretion of EGFP from the 3T3-L1 adipocytes transfected with blank pEGFP-N1 vector could not be detected, suggesting that the EGFP-tagged adipokines were likely released through the endogenous secretory pathways. The effects of GPI and forskolin on secretion of leptin-EGFP (Fig. 4C) and resistin-EGFP (Fig. 4D) are consistent with their effects on trafficking of leptin and resistin vesicles (Fig. 3), and with western blot results of endogenous leptin and resistin secretion (see section below). All these observations indicate that the overexpressed leptin-EGFP and resistin-EGFP are packed in the endogenous vesicles, and regulated similarly as the endogenous proteins.

Secretion of leptin and resistin is differentially regulated

Western blot was used to assay the secretion of endogenous leptin and resistin from 3T3-L1 adipocytes. The top panel of Fig. 5A (B) presents western blots of leptin (resistin) secretion from control cells or cells treated with different chemicals (GPI, forskolin, leptin, or resistin). The bottom panels of Fig. 5A and B present the statistics (mean \pm S.E.M.) of the western blots quantified by optical density from five to six

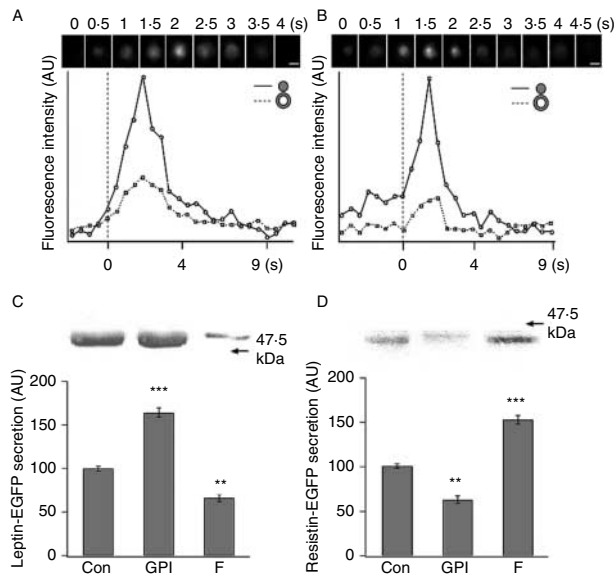


Figure 4 Leptin-EGFP and resistin-EGFP molecules are packed into fusion-competent vesicles. (A and B) Sequential images of full fusion event (top) of a leptin-EGFP vesicle (A) and a resistin-EGFP vesicle (B). The scale bars = 1 μ m. The curves in the bottom panel represent the change of the mean fluorescence intensity over time within the region <0.5 μ m away from the vesicle center (solid line) and the change of fluorescence intensity within the annular region >0.5 and <0.65 μ m away from the vesicle center (dotted line). Full fusion of vesicle is characterized by simultaneous transient increase in these two curves due to rapid release of the fluorescent molecules and their diffusion to the peripheral region (Bai *et al.* 2007). (C and D) Western blots of leptin-EGFP (C) and resistin-EGFP (D) secretion under control condition, or in presence of 10 μ M forskolin (F), GPI. The 3T3-L1 adipocytes were transfected with leptin-EGFP or resistin-EGFP plasmids, 3–4 days before the experiments. Then the 3T3-L1 adipocyte culture was refreshed with the serum-free medium, and the medium with secreted leptin-EGFP protein and resistin-EGFP protein was collected 2 h later for western blot. Top panel shows example western blots. The bottom panel shows the statistics (mean \pm S.E.M.) obtained from three to four independent experiments. The values are optical density of the blots in arbitrary unit. Student's *t*-test: ** P <0.01, *** P <0.001 versus control.

independent experiments. The western blot assays of secretion agree well with the observations on vesicle trafficking, i.e. all the treatments similarly affect vesicle trafficking and actual secretion. These corroborate the notions that leptin-EGFP- and resistin-EGFP-labeled vesicles are endogenous vesicles, and trafficking of leptin and resistin vesicles is intimately related to the actual secretion of these adipokines.

Consistent with the previous study (Levy & Stevens 2001), Fig. 5A demonstrates that leptin secretion occurred in the absence of any stimulation, and it was potently stimulated by the application of GPI. Therefore, it appears that leptin secretion is achieved through both constitutive and regulated secretory pathways. The constitutive secretion of leptin was greatly reduced by forskolin. In addition, GPI-stimulated

secretion of leptin was completely abolished by forskolin, agreeing with the previous reports (Alonso-Vale *et al.* 2005).

Resistin also undertakes both constitutive and regulated secretory pathways (Fig. 5B). GPI and forskolin regulate resistin secretion in the ways opposite to their influences on leptin secretion. Specifically, it was observed that forskolin increased resistin secretion, whereas GPI reduced it. Therefore, in line with our observations on vesicle trafficking, insulin/glycolytic substrates and cAMP/PKA differentially regulate leptin and resistin secretion. The complete elimination of the GPI effects (its facilitation in leptin secretion and inhibition in resistin secretion) by forskolin suggests that cAMP/PKA may act downstream of insulin in the regulated secretory pathways of both leptin and resistin. Also in agreement with the results on vesicle trafficking, leptin and resistin antagonized each other on secretion. In other words, application of resistin in the medium inhibited leptin secretion, and on the other hand, application of leptin suppressed resistin secretion (Fig. 5).

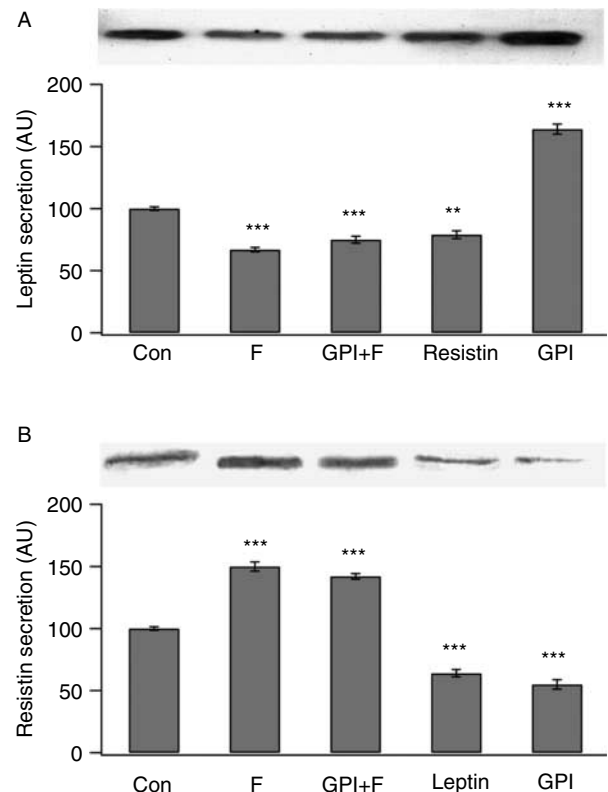


Figure 5 Western blots of leptin (A) and resistin (B) secretion under control condition (Con), or in presence of 10 μ M forskolin (F), 10 μ M forskolin plus GPI (GPI+F), 0.1 μ M leptin or resistin, GPI. The 3T3-L1 adipocyte culture was refreshed with the serum-free medium, and the medium with secreted leptin and resistin was collected 2 h later for western blot. Top panel shows example western blots. The bottom panel shows the statistics (mean \pm S.E.M.) obtained from five to six independent experiments. The values are optical density of the blots in arbitrary unit. Student's *t*-test: ** P <0.01, *** P <0.001 versus control.

Calcium dependence of leptin and resistin secretion

Regulated vesicular secretion is usually calcium dependent. A classic example is neurotransmitter release from SVs in neurons. Increase of intracellular free Ca^{2+} by Ca^{2+} influx through voltage-dependent Ca^{2+} channels is required to drive fusion of the readily releasable vesicles with the plasma membrane, and to dock the prime vesicles into readily releasable state, by triggering rapid actions of secretory proteins (Burgoyne & Morgan 2003). Although such Ca^{2+} triggering mechanism is obviously beneficial to ensure rapid neurotransmission, neuroendocrine cells also share the similar mechanism to release hormones from LDCVs into circulation (Burgoyne & Morgan 2003, Xue *et al.* 2009a). Are GPI-stimulated leptin secretion and forskolin-stimulated resistin secretion calcium dependent? To address this question, western blot of leptin and resistin secretion was performed, with or without depletion of extracellular Ca^{2+} , with or without depletion of intracellular Ca^{2+} , and with or without GPI or forskolin stimulation (Fig. 6A–D). It was found that both basal and GPI-stimulated leptin secretion were significantly suppressed when external calcium was depleted by calcium chelator EGTA, or when internal calcium was depleted by membrane permeable calcium chelator BAPTA-AM. Therefore, both constitutive and regulated leptin secretion are Ca^{2+} dependent. In contrast, only basal, but not forskolin-stimulated, resistin secretion depends significantly on Ca^{2+} .

As expected from the observation that Ca^{2+} depletion did not inhibit forskolin-stimulated resistin secretion, forskolin did not trigger any Ca^{2+} signal based on Ca^{2+} photometry measurement (Fig. 6E). But surprisingly, despite that GPI-stimulated leptin secretion requires Ca^{2+} , GPI was also not able to elicit any acute increase in cytosolic free Ca^{2+} . Similar observation was reported in primary rat adipocytes (Kelly *et al.* 1989). It implies that GPI stimulates leptin secretion not through acute increase in intracellular Ca^{2+} concentration. It is worth pointing out that Ca^{2+} imaging (Fig. 6E) was undertaken in a time scale of minutes, while the secretion of adipokines was measured in 2 h (Fig. 5). Thus, the possibility that GPI and forskolin may modulate intracellular Ca^{2+} in a slow rate cannot be ruled out. Taken together, external and internal calcium are important for both basal and regulated leptin secretions, and for basal resistin secretion. As a control experiment, application of calcium ionophore calcimycin resulted in sharp increase in $[\text{Ca}^{2+}]_i$ (Fig. 6E). Interestingly, high K^+ solution which depolarizes the cell membrane also caused increase of $[\text{Ca}^{2+}]_i$, albeit with slow rise compared to the responses in excitable cells such as neurons and neuroendocrine cells which have abundant voltage-gated Ca^{2+} channels. This observation may suggest the existence of slowly activated voltage-gated Ca^{2+} channels or Ca^{2+} carriers in 3T3-L1 adipocytes that may be involved in the calcium-dependent secretion of adipokines.

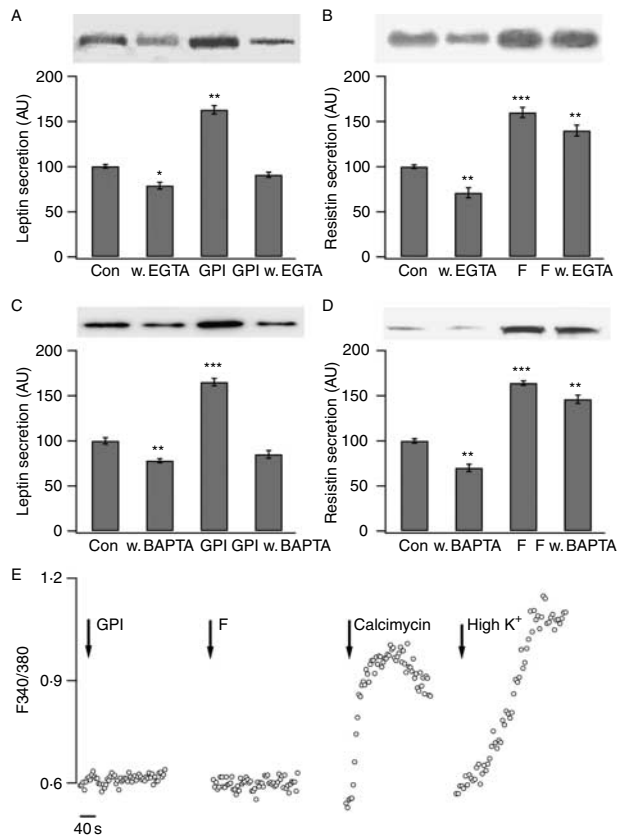


Figure 6 Calcium dependence of leptin and resistin secretion. (A–D) Example western blots (top) and statistics (bottom: mean \pm S.E.M.) from three to four independent experiments quantified by optical density of the blots of leptin (A and C) and resistin (B and D) secretion. In A and B, 3T3-L1 adipocyte culture was furnished with the fresh serum-free medium containing 1.8 mM Ca^{2+} , without (Con) or with 10 mM Ca^{2+} chelator EGTA (w. EGTA), or with stimulation (GPI or forskolin denoted as F), or with stimulation and with EGTA (GPI w. EGTA and F w. EGTA). In C and D, 3T3-L1 adipocytes were incubated without or with membrane permeable Ca^{2+} chelator BAPTA-AM (50 μM) for 15 min (w. BAPTA) in the calcium-free bath solution. The cells were then washed and incubated with the fresh serum-free medium containing 1.8 mM Ca^{2+} , without stimulation (Con), or with stimulation (GPI or F). The medium with secreted leptin and resistin was collected 2 h later for western blot. Student's *t*-test: * $P < 0.05$, ** $P < 0.01$ and *** $P < 0.001$ versus Con. (E) Typical recordings of intracellular Ca^{2+} concentration from 3T3-L1 adipocyte in response to GPI, forskolin, calcimycin, and high K^+ stimulation (from left to right). The Ca^{2+} concentration is reported by the ratio between the intensities of fluorescence emission when the Ca^{2+} sensitive dye (Fura2) is excited at 340 and 380 nm.

Discussion

It has been well documented that leptin and resistin are adipocyte-derived polypeptide hormones implicated critically in metabolic homeostasis (Rondinone 2006, Rosen & Spiegelman 2006, Lago *et al.* 2009). The functions and the secretory pathways of these adipokines, however, are still

poorly understood. Particularly, very little is known about resistin. In the present work, we provide evidences that, in 3T3-L1 adipocytes, 1) leptin and resistin are compartmentalized into different vesicles, and these vesicles are distinct to early endosomes and Glut4-containing vesicles; 2) in addition to constitutive secretion, both adipokines are released through regulated secretion, likely, regulated vesicular exocytosis, because all the reagents that we tested affect their secretion and vesicle trafficking similarly; 3) the vesicle trafficking and secretion of leptin and resistin are differentially regulated by insulin/glycolytic substrates and PKA; 4) constitutive secretion of both leptin and resistin are Ca^{2+} dependent, and GPI-stimulated secretion of leptin, but not forskolin-stimulated secretion of resistin, is Ca^{2+} dependent, despite that GPI cannot induce acute increase of $[\text{Ca}^{2+}]_i$; and 5) interplays exist between these two adipokines. Specifically, they are all subject to regulations by insulin/glycolytic substrates, cAMP and Ca^{2+} ; and leptin and resistin antagonize each other on vesicle trafficking and secretion.

Studies have been carried out to identify the vesicular carriers responsible for the accumulation and transport of leptin. Using density and velocity gradient centrifugation (Roh *et al.* 2000, 2001), immunofluorescence confocal microscopy (Barr *et al.* 1997, Roh *et al.* 2001), and electron microscopy based on immunolabeling (Bornstein *et al.* 2000), it has been revealed that leptin molecules aggregate into low-density vesicles whose molecular identity is unknown, and that leptin-containing vesicles are distinct from vesicles that contain Glut4 (Barr *et al.* 1997, Roh *et al.* 2000), or lipoprotein lipase (Roh *et al.* 2001), or adiponectin (another adipokine; Xie *et al.* 2008). To our best knowledge, vesicular compartmentalization of resistin has not yet been reported.

Here, confocal imaging based on immunostaining and TIRFM imaging on live 3T3-L1 adipocytes overexpressed with fluorescent leptin or resistin revealed that these adipokines are packed into numerous vesicles. These vesicles are not identical to Glut4-containing vesicles that are also sensitive to insulin and not identical to endosomes that often involve in the exocytotic pathways. It appears that these vesicles are similar to hormone-containing secretory vesicles in endocrine cells such as chromaffin cells (Gasman *et al.* 1997, Steyer *et al.* 1997) and chromaffin-derived PC12 cells (Zhang *et al.* 2008) in terms of size and characteristics in trafficking. In addition, reagents that stimulate (or inhibit) the secretion of these adipokines also facilitate (or reduce) its vesicle trafficking. These observations support the view that these adipokines can be released through regulated vesicular exocytosis.

Whether adipokines are released by constitutive secretion or regulated secretion (exocytosis) or both is still a question under scrutiny. In constitutive pathways, secretory compounds are continuously secreted at a rate proportional to its synthesis without the need of stimulation, whereas, in regulated exocytotic pathways, proteins are stored into secretory vesicles and are discharged rapidly into extracellular

space only in response to specific stimulations. Constitutive (basal) secretion of adipokines is presumably needed to set the basal metabolic activities. For example, basal leptin level is necessary to suppress appetite (or to avoid constant hunger). Our results show that both leptin and resistin are constitutively secreted. On the other hand, leptin and resistin also utilize regulated secretory pathways (vesicular exocytosis), because there are a large number of vesicular storage, and GPI or forskolin can acutely stimulate or inhibit secretion and vesicle trafficking of these adipokines (within 2 h for western blot experiments and within 30 min for TIRFM imaging). Regulated secretion of adipokines is presumably important for acute response to metabolic conditions. For example, in response to hyperinsulinemia after a meal or other stimuli, leptin secretion is greatly enhanced as a signal of nutritional status to the hypothalamus thereby increasing insulin sensitivity, inhibiting food intake, enhancing energy expenditure, and regulating body fat.

Co-immunostaining of endogenous leptin and resistin showed that these adipokines are accumulated in different types of vesicles. Their distinct identities were further confirmed by immunostaining of endogenous resistin in leptin-EGFP overexpressed cells and by immunostaining of endogenous leptin in resistin-EGFP overexpressed cells (Supplementary Figure 1, see section on supplementary data given at the end of this article). The different compartmentalization implies that they are secreted through distinct pathways. Indeed, we found that the secretion and vesicle trafficking of leptin and resistin are oppositely modulated by insulin/glycolytic substrates and cAMP/PKA.

It has been shown that insulin upgrades leptin expression (Barr *et al.* 1997) and downgrades resistin expression (Haugen *et al.* 2001, Shojima *et al.* 2002, Chen *et al.* 2005). But the acute effects we observed are likely resulting from facilitation of regulated vesicular secretion of pre-stored adipokines instead of increased protein synthesis. Although GPI increased leptin expression and forskolin increased resistin expression in 3T3-L1 adipocytes (Supplementary Figure 2, see section on supplementary data given at the end of this article), application of a protein synthesis inhibitor (cycloheximide), which completely eliminated GPI- and forskolin-induced protein synthesis, was not able to block the GPI-enhanced leptin secretion or forskolin-enhanced resistin secretion (Supplementary Figure 3, see section on supplementary data given at the end of this article). In addition, cycloheximide could not block the effects of forskolin and resistin on leptin secretion or the effects of GPI and leptin on resistin secretion (Supplementary Figure 3). In agreement with our study, Bradley & Cheatham (1999) also showed that insulin stimulates leptin secretion from a pre-existing intracellular pool in rat primary adipocytes.

It is not surprising that the two adipokines are regulated differently and inhibit each other, considering that they counteract in some metabolic regulations such as insulin sensitivity and gluconeogenesis (Rossetti *et al.* 1997, Ogawa *et al.* 1999, Stepan *et al.* 2001, Banerjee *et al.* 2004).

The functional links between leptin and resistin have been revealed by several studies which showed that leptin treatment decreased resistin expression in ob/ob mice (Asensio *et al.* 2004, Rajala *et al.* 2004), and loss of resistin improved glucose homeostasis in leptin deficiency (Qi *et al.* 2006). Here, we show that leptin and resistin inhibit trafficking and secretion of each other at autocrine level. Intuitively, the autocrine regulations are important to the autoregulation of the fat mass and to balance the actions of various adipokines in response to complex metabolic signaling. Although leptin receptors in the hypothalamus is considered as the major mediator of leptin functions, leptin receptors have been found ubiquitously in most other tissues including adipose (Kielar *et al.* 1998). This suggests a universal, although not fully understood, role of leptin at autocrine, paracrine, and endocrine levels. But the putative resistin receptors have not yet been identified.

The role of calcium on leptin secretion has been studied previously in primary rat adipocytes (Levy *et al.* 2000, Cammisotto & Bukowiecki 2004). In contrast to our observation in 3T3-L1 adipocytes, these studies found that basal leptin secretion is calcium independent. On the other hand, these studies and ours all indicated that insulin-stimulated leptin secretion is calcium dependent. However, we show that insulin is not able to elicit acute increase in $[Ca^{2+}]_i$, agreeing with the previous report (Kelly *et al.* 1989). This seems contradictory to the calcium dependence of GPI-stimulated leptin secretion as observed in western blot and trafficking of leptin vesicles. Such contradiction was also reported by Cammisotto & Bukowiecki (2004) in primary rat adipocytes. These authors argued that external calcium is needed for insulin-stimulated leptin secretion by enhancing glucose uptake although insulin does not affect extracellular calcium uptake. It is also conceivable that depletion of external calcium could gradually lead to a lower basal intracellular concentration, which, in turn, may affect glucose uptake, or directly affect the constitutive and regulated secretory pathways. It has been shown that depleting intracellular Ca^{2+} using BAPTA-AM diminishes >95% of insulin-stimulated glucose uptake by reducing the translocation as well as the final fusion steps of Glut4 (Whitehead *et al.* 2001). In comparison to leptin secretion, basal resistin secretion is also calcium dependent, while forskolin-stimulated resistin secretion does not require calcium uptake. Clearly, calcium regulation on leptin and resistin secretion from adipocytes is markedly different from that on vesicular exocytosis in neurons and neuroendocrine cells.

In summary, we have comparatively studied several key aspects of leptin and resistin secretion, specifically, vesicle storage, vesicle trafficking, insulin/glycolytic substrates and cAMP/PKA regulation. Further investigations are certainly required to reveal the similarities, differences, and interplays between the secretory pathways of all adipokines in order to understand how they act synergistically or antagonizingly in response to complex metabolic signals.

Supplementary data

This is linked to the online version of the paper at <http://dx.doi.org/10.1677/JOE-10-0090>.

Declaration of interest

The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of this scientific work.

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References

- Alonso-Vale MIC, Andreotti S, Peres SB, Anhe GF, Borges-Silva CD, Neto JC & Lima FB 2005 Melatonin enhances leptin expression by rat adipocytes in the presence of insulin. *American Journal of Physiology. Endocrinology and Metabolism* **288** E805–E812.
- Anagnostoulis S, Karayiannakis AJ, Lambropoulou M, Efthimiadou A, Polychronidis A & Simopoulos C 2008 Human leptin induces angiogenesis *in vivo*. *Cytokine* **42** 353–357.
- Asensio C, Cettour-Rose P, Theander-Carrillo C, Rohner-Jeanrenaud F & Muzzin P 2004 Changes in glycemia by leptin administration or high-fat feeding in rodent models of obesity/type 2 diabetes suggest a link between resistin expression and control of glucose homeostasis. *Endocrinology* **145** 2206–2213.
- Bai L, Wang Y, Fan JM, Chen Y, Ji W, Qu AL, Xu PY, James DE & Xu T 2007 Dissecting multiple steps of GLUT4 trafficking and identifying the sites of insulin action. *Cell Metabolism* **5** 47–57.
- Banerjee RR, Rangwala SM, Shapiro JS, Rich AS, Rhoades B, Qi Y, Wang J, Rajala MW, Pocai A, Scherer PE *et al.* 2004 Regulation of fasted blood glucose by resistin. *Science* **303** 1195–1198.
- Barr VA, Malide D, Zarnowski MJ, Taylor SI & Cushman SW 1997 Insulin stimulates both leptin secretion and production by rat white adipose tissue. *Endocrinology* **138** 4463–4472.
- Bornstein SR, Abu-Asab M, Glasow A, Path G, Hauner H, Tsokos M, Chrousos GP & Scherbaum WA 2000 Immunohistochemical and ultrastructural localization of leptin and leptin receptor in human white adipose tissue and differentiating human adipose cells in primary culture. *Diabetes* **49** 532–538.
- Bouloumie A, Drexler HCA, Lafont M & Busse R 1998 Leptin, the product of Ob gene, promotes angiogenesis. *Circulation Research* **83** 1059–1066.
- Bradley RL & Cheatham B 1999 Regulation of ob gene expression and leptin secretion by insulin and dexamethasone in rat adipocytes. *Diabetes* **48** 272–278.
- Burgoyne RD & Morgan A 2003 Secretory granule exocytosis. *Physiological Reviews* **83** 581–632.
- Cammisotto PG & Bukowiecki LJ 2004 Role of calcium in the secretion of leptin from white adipocytes. *American Journal of Physiology. Regulatory, Integrative and Comparative Physiology* **287** R1380–R1386.
- Chen P & Gillis KD 2000 The noise of membrane capacitance measurements in the whole-cell recording configuration. *Biophysical Journal* **79** 2162–2170.
- Chen YH, Hung PF & Kao YH 2005 IGF-I downregulates resistin gene expression and protein secretion. *American Journal of Physiology. Endocrinology and Metabolism* **288** E1019–E1027.
- Dal Rhee S, Sung YY, Jung WH & Cheon HG 2008 Leptin inhibits rosiglitazone-induced adipogenesis in murine primary adipocytes. *Molecular and Cellular Endocrinology* **294** 61–69.

- Degtyar VE, Allersma MW, Axelrod D & Holz RW 2007 Increased motion and travel, rather than stable docking, characterize the last moments before secretory granule fusion. *PNAS* **104** 15929–15934.
- Gasman S, ChasserotGolaz S, Popoff MR, Aunis D & Bader MF 1997 Trimeric G proteins control exocytosis in chromaffin cells – G(o) regulates the peripheral actin network and catecholamine secretion by a mechanism involving the small GTP-binding protein Rho. *Journal of Biological Chemistry* **272** 20564–20571.
- Haugen F, Jorgensen A, Drevon CA & Trayhurn P 2001 Inhibition by insulin of resistin gene expression in 3T3-L1 adipocytes. *FEBS Letters* **507** 105–108.
- Holz RW & Axelrod D 2008 Secretory granule behaviour adjacent to the plasma membrane before and during exocytosis: total internal reflection fluorescence microscopy studies. *Acta Physiologica* **192** 303–307.
- Kelly KL, Deeney JT & Corkey BE 1989 Cytosolic free calcium in adipocytes – distinct mechanisms of regulation and effects on insulin action. *Journal of Biological Chemistry* **264** 12754–12757.
- Kielar D, Clark JSC, Ciechanowicz A, Kurzawski G, Sulikowski T & Naruszewicz M 1998 Leptin receptor isoforms expressed in human adipose tissue. *Metabolism: Clinical and Experimental* **47** 844–847.
- Kim KH, Lee K, Moon YS & Sul HS 2001 A cysteine-rich adipose tissue-specific secretory factor inhibits adipocyte differentiation. *Journal of Biological Chemistry* **276** 11252–11256.
- Kolaczynski JW, Considine RV, Ohannesian J, Marco C, Opentanova I, Nycze MR, Myint M & Caro JF 1996 Responses of leptin to short-term fasting and refeeding in humans – a link with ketogenesis but not ketones themselves. *Diabetes* **45** 1511–1515.
- Lago F, Dieguez C, Gomez-Reino J & Gualillo O 2007 Adipokines as emerging mediators of immune response and inflammation. *Nature Clinical Practice. Rheumatology* **3** 716–724.
- Lago F, Gomez R, Gomez-Reino JJ, Dieguez C & Gualillo O 2009 Adipokines as novel modulators of lipid metabolism. *Trends in Biochemical Sciences* **34** 500–510.
- Levy JR & Stevens W 2001 The effects of insulin, glucose, and pyruvate on the kinetics of leptin secretion. *Endocrinology* **142** 3558–3562.
- Levy JR, Gyarmati J, Lesko JM, Adler RA & Stevens W 2000 Dual regulation of leptin secretion: intracellular energy and calcium dependence of regulated pathway. *American Journal of Physiology. Endocrinology and Metabolism* **278** E892–E901.
- Minokoshi Y, Kim YB, Peroni OD, Fryer LGD, Muller C, Carling D & Kahn BB 2002 Leptin stimulates fatty-acid oxidation by activating AMP-activated protein kinase. *Nature* **415** 339–343.
- Mu H, Ohashi R, Yan SY, Chai H, Yang H, Lin P, Yao QZ & Chen CY 2006 Adipokine resistin promotes *in vitro* angiogenesis of human endothelial cells. *Cardiovascular Research* **70** 146–157.
- Ogawa Y, Masuzaki H, Hosoda K, Aizawa-Abe M, Suga J, Suda M, Ebihara K, Iwai H, Matsuoka N, Satoh N *et al.* 1999 Increased glucose metabolism and insulin sensitivity in transgenic skinny mice overexpressing leptin. *Diabetes* **48** 1822–1829.
- Palanivel R & Sweeney G 2005 Regulation of fatty acid uptake and metabolism in L6 skeletal muscle cells by resistin. *FEBS Letters* **579** 5049–5054.
- Qi Y, Nie ZY, Lee YS, Singhal NS, Scherer PE, Lazar MA & Ahima RS 2006 Loss of resistin improves glucose homeostasis in leptin deficiency. *Diabetes* **55** 3083–3090.
- Rajala MW, Qi Y, Patel HR, Takahashi N, Banerjee R, Pajvani UB, Sinha MK, Gingerich RL, Scherer PE & Ahima RS 2004 Regulation of resistin expression and circulating levels in obesity, diabetes, and fasting. *Diabetes* **53** 1671–1679.
- Reilly MP, Lehrke M, Wolfe ML, Rohatgi A, Lazar MA & Rader DJ 2005 Resistin is an inflammatory marker of atherosclerosis in humans. *Circulation* **111** 932–939.
- Roh C, Thodis G, Farmer SR & Kandror KV 2000 Identification and characterization of leptin-containing intracellular compartment in rat adipose cells. *American Journal of Physiology. Endocrinology and Metabolism* **279** E893–E899.
- Roh C, Roduit R, Thorens B, Fried S & Kandror KV 2001 Lipoprotein lipase and leptin are accumulated in different secretory compartments in rat adipocytes. *Journal of Biological Chemistry* **276** 35990–35994.
- Rondinone CM 2006 Adipocyte-derived hormones, cytokines, and mediators. *Endocrine* **29** 81–90.
- Rosen ED & Spiegelman BM 2006 Adipocytes as regulators of energy balance and glucose homeostasis. *Nature* **444** 847–853.
- Rossetti L, Massillon D, Barzilai N, Vuguin P, Chen W, Hawkins M, Wu J & Wang JL 1997 Short term effects of leptin on hepatic gluconeogenesis and *in vivo* insulin action. *Journal of Biological Chemistry* **272** 27758–27763.
- Shao DL & Lazar MA 1997 Peroxisome proliferator activated receptor gamma, CCAAT/enhancer-binding protein alpha, and cell cycle status regulate the commitment to adipocyte differentiation. *Journal of Biological Chemistry* **272** 21473–21478.
- Shojima N, Sakoda H, Ogihara T, Fujishiro M, Katagiri H, Anai M, Onishi Y, Ono H, Inukai K, Abe M *et al.* 2002 Humoral regulation of resistin expression in 3T3-L1 and mouse adipose cells. *Diabetes* **51** 1737–1744.
- Steppan CM, Bailey ST, Bhat S, Brown EJ, Banerjee RR, Wright CM, Patel HR, Ahima RS & Lazar MA 2001 The hormone resistin links obesity to diabetes. *Nature* **409** 307–312.
- Steyer JA, Horstmann H & Almers W 1997 Transport, docking and exocytosis of single secretory granules in live chromaffin cells. *Nature* **388** 474–478.
- Trujillo ME & Scherer PE 2006 Adipose tissue-derived factors: impact on health and disease. *Endocrine Reviews* **27** 762–778.
- Whitehead JP, Molero JC, Clark S, Martin S, Meneilly G & James DE 2001 The role of Ca²⁺ in insulin-stimulated glucose transport in 3T3-L1 cells. *Journal of Biological Chemistry* **276** 27816–27824.
- Xie LL, O'Reilly CP, Chapes SK & Mora S 2008 Adiponectin and leptin are secreted through distinct trafficking pathways in adipocytes. *Biochimica et Biophysica Acta* **1782** 99–108.
- Xue RH, Zhao YY & Chen P 2009a Involvement of PKC alpha in PMA-induced facilitation of exocytosis and vesicle fusion in PC12 cells. *Biochemical and Biophysical Research Communications* **380** 371–376.
- Xue RH, Zhao YY, Su LY, Ye F & Chen P 2009b PKC epsilon facilitates recovery of exocytosis after an exhausting stimulation. *Pflügers Archiv: European Journal of Physiology* **458** 1137–1149.
- Zhang EM, Xue RH, Soo J & Chen P 2008 Effects of phorbol ester on vesicle dynamics as revealed by total internal reflection fluorescence microscopy. *Pflügers Archiv: European Journal of Physiology* **457** 211–222.
- Zhou YT, Wang ZW, Higa M, Newgard CB & Unger RH 1999 Reversing adipocyte differentiation: implications for treatment of obesity. *PNAS* **96** 2391–2395.
- Zhou KM, Dong YM, Ge Q, Zhu D, Zhou W, Lin XG, Liang T, Wu ZX & Xu T 2007 PKA activation bypasses the requirement for UNC-31 in the docking of dense core vesicles from *C. elegans* neurons. *Neuron* **56** 657–669.

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