EXPERIMENTAL STUDY

Resistin promotes 3T3-L1 preadipocyte differentiation

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Abstract

Objective: To investigate the relationship between resistin (a potential link between obesity and type 2 diabetes) and preadipocyte differentiation.

Design: A rat resistin expression vector was transfected into 3T3-L1 preadipocytes and differentiation was compared between normal 3T3-L1 cells, rat resistin-transfected cells and non-transfected cells grown in conditioned medium taken from resistin-expressing cultures.

Methods: The rat resistin gene was inserted into the pDual GC and pEFGP-N2 expression vectors for examination of the effects of resistin overexpression in 3T3-L1 cells before and after differentiation was stimulated with 3-isobutyl-1-methyxanthine (MIX), insulin and dexamethasone (DEX). Smaller conserved fragments were inserted into short interference RNA (siRNA) expression vectors, for examination of the effect of targeted resistin inhibition on differentiation of resistin-overexpressing 3T3-L1 cells.

Results: Prior to stimulation, the resistin-transfected 3T3-L1 cells contained many more small lipid droplets than did non-transfected 3T3-L1 cells. Following stimulation, differentiation in the resistin-transfected 3T3-L1 cells was dramatically promoted, especially in the early stages. Stimulation of differentiation was also observed in non-transfected 3T3-L1 cells grown in resistin protein-containing conditioned medium. The expression of adipocyte differentiation-associated markers such as CCAAT enhancer binding protein (C/EBPα), retinoid X receptor (RXRα) and lipoprotein lipase (LPL) was upregulated in resistin-overexpressing cells, whereas expression of preadipocyte factor-1 (Pref-1), an inhibitor of preadipocyte differentiation, was downregulated. In addition, expression of two of the three tested siRNAs inhibited the adipoconversion process, providing further evidence that resistin promotes the differentiation of preadipocytes to adipocytes.

Conclusion: Resistin can promote preadipocyte differentiation. Based on this, we propose that resistin may be an important candidate mediator of obesity-induced insulin resistance.

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Introduction

Adipocytes secrete a number of molecules that are capable of influencing cellular responsiveness to insulin (1, 2). Resistin, a novel cysteine-rich secretory signaling molecule, was recently identified as a member of the diverse family of adipocyte-derived polypeptides that may link obesity and type 2 diabetes mellitus (3). Serum resistin levels were markedly increased in both diet-induced and genetically obese mice; these levels were decreased by treatment with rosiglitazone, an anti-diabetic drug that can enhance insulin sensitivity (3). Serum resistin levels were markedly increased in both diet-induced and genetically obese mice; these levels were decreased by treatment with rosiglitazone, an anti-diabetic drug that can enhance insulin sensitivity (3). Resistin treatment of normal mice impaired glucose tolerance, whereas immunoneutralization of the resistin protein in mice increased insulin sensitivity (3). Moreover, resistin is expressed mainly in adipose tissues, and was found to be significantly upregulated during the differentiation of preadipocytes to mature adipocytes (4). Surprisingly, both resistin and resistin-like molecules have been reported to inhibit preadipocyte differentiation (4, 5). Overall, these findings suggest that resistin plays a role in preadipocyte differentiation, and may be involved in the molecular mechanisms by which increased adiposity causes insulin resistance and type 2 diabetes.

To explore the function of resistin in the process of preadipocyte differentiation (adipoconversion), we cloned the rat resistin gene into the pDual GC vector for expression of a resistin fusion protein containing a thrombin cleavage site, three c-myc epitope tags and a 6×His tag. This construct was stably transfected into 3T3-L1 cells, which were found to differentiate much more quickly than non-transfected 3T3-L1 cells. We hypothesized that secreted resistin inhibits
preadipocyte differentiation, whereas partial intercellular resistin could be transported into the nucleus to act as a pro-differentiation transcription through its predicted leucine zipper motif. To address this, we constructed a pEGFP-N2-resistin expression vector and used this to examine the subcellular location of resistin before and during adipoconversion. To further confirm that resistin could promote preadipocyte differentiation, we next identified three short resistin regions (19 bp or longer) which are conserved between the rat and mouse genes, and used these as targets for RNA interference (RNAi). As a sequence-specific post-transcriptional gene silencing technique, RNAi has proven to be a powerful technology for elucidating gene function (6, 7). Consistent with our other results, transfection of two of the three siRNA expression vectors inhibited 3T3-L1 preadipocyte differentiation, suggesting that decreased resistin function led to decreased promotion of differentiation. Taken together, our results indicate that resistin could be a powerful technology for elucidating gene function.

Materials and methods

Construction of resistin expression plasmids
A full-length cDNA encoding the rat resistin gene was prepared by reverse transcriptase (RT)-PCR amplification using the following primers: sense, 5'-CGCTCTTCGATGAAGAACCTTTCATTTCTC-3' and antisense, 5'-CGCTCTTCCAGGGGACCAAGCCGCAAGGTAC-3' (for insertion into the pDual GC expression vector (Stratagene, Germany)); and sense, 5'-GATCTCGAGAT-CCCAGAAGGCA-3' or EcoRI and XhoI for ligation into HindIII- and BamHI-digested pEGFP-N2 subcellular location expression vector (Clontech). The resultant PCR products were digested with Eam1104I (a type IIS restriction enzyme capable of cutting outside its recognition sequence, 5'-CTCTTC-3') or EcoRI and Xhol for ligation into pDual GC or pEGFP-N2 respectively. Figure 1 illustrates schematically the relevant recognition sequences and cleavage sites of Eam1104I. The resultant plasmids were confirmed by sequencing; the predicted molecular weight of the resistin-6×His fusion protein was 22.377 kDa (not including the signal peptide).

**Figure 1** Recognition sequence (5'-CTCTTC-3') and cleavage sites of the restriction enzyme Eam1104I. Eam1104I is a type IIS restriction enzyme capable of cutting outside its recognition sequence (5'-CTCTTC-3').

Construction of resistin short interference RNA (siRNA) expression plasmids
siRNA consisting of two hybridized 21 mer RNA molecules with 19 complementary nucleotides and 3' terminal dinucleotide overhangs has been found to effectively trigger sequence-specific mRNA degradation (8, 9). Accordingly, BLAST 2 homology searching was used to identify three conserved cDNA fragments (>18 bp) within the coding region of the rat and mouse resistin genes. From these sequences, we designed and synthesized three pairs of reverse complementary oligonucleotides, each containing a loop sequence (5'-TTCAAGAGA-3'), the RNA PloIII terminator (5'-TTTTTTT-3') and 5' single-stranded overhangs for ligation into HindIII- and BamHI-digested pSilencer 2.0-U6 vectors (Ambion, USA). These oligonucleotides were annealed and inserted into the siRNA expression vectors as shown schematically in Fig. 2. The sequences of the three cDNA fragments (sense strands) were as follows: (1) 5'-CCCTTTTATTCTCTCTTT-3'; (2) 5'-AGCTGCTCTGGTGGCTCTG-3'; (3) 5'-GCTCTCTGTCGCAGGCA-3'. These were used to create pSilencer 2.0-U6-resistin1, pSilencer 2.0-U6-resistin2 and pSilencer 2.0-U6-resistin3 respectively. An insert control designed to target GAPDH mRNA was used as the positive control (Ambion). An insert-free 2.0-U6 vector served as the negative control.

Transfection and selection of 3T3-L1 cells stably expressing exogenous resistin
For stable expression of the rat resistin gene, the pDual GC-resistin or pEGFP-resistin expression vectors were transfected into 3T3-L1 cells using Fugene 6 (Roche), and transfected cells were selected for 2 weeks in medium containing 800 mg/ml G418 (geneticin). The surviving cells were screened for resistin expression by Western blotting of the cell culture supernatants, using anti-6×His or anti-green fluorescence protein (GFP) antibodies respectively, and then further grown in culture medium supplemented with 300 μg/ml G418.

T3-L1 cell culture and induction of differentiation
3T3-L1 preadipocytes were cultured and induced to differentiate as previously described (5). In short, cells were cultured in Dulbecco’s modified Eagle’s medium (DMEM) containing 10% fetal bovine serum (FBS) in 5% CO2 at 37°C. Two days after complete confluence was reached (day 0), differentiation was induced when we changed the medium to DMEM containing 10% FBS plus 0.5 mM 3-isobutyl-1-methoxanthine (MINX) (Sigma), 1 μg/ml insulin (Sigma) and 1 μM dexamethasone (Sigma). After 48 h (day 2), the medium was replaced with DMEM containing 10% FBS plus 1 μg/ml insulin. On day 4, the medium was replaced with DMEM containing only 10% FBS, and then was changed.
with the same medium every 2 days thereafter. Conditioned culture medium collected from pDual GC-resistin stably transfected 3T3-L1 cells cultured without G418 for 48 h was centrifuged at 500 g for 5 min and stored at 4 °C for less than a week before use. For experiments involving conditioned medium, cells were cultured in 50% conditioned medium and 50% DMEM containing 10% FBS.

**Oil Red O staining** Cells were stained with Oil Red O and hematoxylin as described previously (10). Briefly, 10% formalin (pH 7.4)-fixed 3T3-L1 cells were stained by Oil Red O (stock solution: 3 mg/ml dissolved in isopropanol; working solution: 60% Oil Red O stock solution and 40% distilled water) for 5 min and then counterstained with hematoxylin for 1 min.

**RNA interference**

Five pSilencer 2.0-U6 vectors including a negative and a positive control were Fugene 6-transfected into untreated or resistin-transfected 3T3-L1 cells, which were then grown in six-well culture plates with complete culture medium. Lipopolysaccharide (LPS)-free vector (2 μg per well) was used for each transfection; the ratio of Fugene 6 to vector was 6:1. Two days (48 h) after transfection, cells and supernatants were collected for RT-PCR and Western blot detection.

**RNA preparation and amplification by RT-PCR**

Total RNA was isolated from 3T3-L1 cells using the TRIZOL method (Invitrogen). One microgram of total RNA was converted to cDNA using 200U Moloney murine leukemia virus RT (Promega), and an aliquot (10%) of the resulting cDNA was amplified with the primers listed in Table 1. The number of cycles and reaction temperatures used in the semiquantitative RT-PCR assay were optimized to provide a linear relationship between the amount of input template and the

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**Table 1** Primers for RT-PCR amplification.

<table>
<thead>
<tr>
<th>Gene name</th>
<th>Product size (bp)</th>
<th>Reverse and forward primer</th>
<th>$T_a$ (°C)</th>
<th>Cycles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rat resistin</td>
<td>396</td>
<td>R: 5'-GCTGTCAGTCTCATTCAAACCGGTCC-3' F: 5'-CTGAGCTCTGTCGACCTACT-3'</td>
<td>64</td>
<td>27</td>
</tr>
<tr>
<td>Mouse resistin</td>
<td>415</td>
<td>R: 5'-CACAAACAACTCACTCCC-3' F: 5'-AGGACACAGCTCTTCTTCTA-3'</td>
<td>58</td>
<td>33</td>
</tr>
<tr>
<td>Mouse FAS</td>
<td>499</td>
<td>R: 5'-GGGACAGAAGACAAAGG-3' F: 5'-TAAAGACCTCCTATGCGCCAACAGT-3'</td>
<td>58</td>
<td>30</td>
</tr>
<tr>
<td>Mouse β-actin</td>
<td>240</td>
<td>R: 5'-CAAGATGGAAGGGGCGCGGACCTGAGT-3' F: 5'-CCACCTCCTATTGTGCGGTCTTCT-3'</td>
<td>57</td>
<td>25</td>
</tr>
<tr>
<td>Mouse C/EBPα</td>
<td>391</td>
<td>R: 5'-AGGATGTCGCGATGAGAG-3' F: 5'-GGGTGGAAGCAGAAGAAGCCACCA-3'</td>
<td>58</td>
<td>30</td>
</tr>
<tr>
<td>Mouse GLUT4</td>
<td>168</td>
<td>R: 5'-GCCGCCCTAAGATTCATGTTGCG-3' F: 5'-CTCCCTCTATTGCGTGCTTCT-3'</td>
<td>58</td>
<td>33</td>
</tr>
<tr>
<td>Mouse Pref-1</td>
<td>272</td>
<td>R: 5'-GCACACGTGCTTCTAACA-3' F: 5'-AGAGCAAACTCCACCAAA-3'</td>
<td>58</td>
<td>30</td>
</tr>
<tr>
<td>Mouse LPL</td>
<td>480</td>
<td>R: 5'-TCTCTGATGACCCAATGTT-3' F: 5'-GGGTGGAAGCAGAAGAAGCCACCA-3'</td>
<td>58</td>
<td>33</td>
</tr>
<tr>
<td>Mouse RXRα</td>
<td>267</td>
<td>R: 5'-CCGGCAATGGTGTAGTCGAGCT-3' F: 5'-CACATTGGGCGCTTCT-3'</td>
<td>65</td>
<td>33</td>
</tr>
</tbody>
</table>

FAS, fatty acid synthetase; C/EBPα, CCAAT enhancer binding protein; Pref-1, preadipocyte factor-1; LPL, lipoprotein lipase; RXRα, retinoid X receptor; R, reverse primer; F, forward primer; $T_a$, annealing temperature.

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**Figure 2** The design of the hairpin siRNA inserts. Resistin cDNA sequences conserved between rat and mouse (longer than 18 bp) were selected and used to design three pairs of reverse complementary oligonucleotides, each containing a loop sequence, the RNA PolIII terminator and 5' single-stranded overhangs for ligation into HindIII- and BamHI-digested pSilencer 2.0-U6 vectors.
amount of PCR product generated over a concentration range from 0.5 to 10 μg total RNA.

**Western blot analysis**

Cultured supernatants of pDual GC-resistin-transfected 3T3-L1 cells and pSilencer 2.0-U6-GAPDH-transfected 3T3-L1 cells were collected. Total proteins were isolated from these cells using the TRIZOL method (Invitrogen), and the protein concentration was determined by BCA assay (Pierce, USA). Total protein (1 μg) was subjected to 12% SDS-PAGE, electro-blotted onto PROTRAN nitrocellulose transfer membranes (Schleicher and Schuell, Germany), and immunodetected using mouse anti-His6 antibody (Clontech) and goat anti-mouse immunoglobulin G (IgG)-horseradish peroxidase conjugate (Amersham) with an ECL Western blot analysis system (Amersham).

**Results**

**Resistin stimulates preadipocyte differentiation**

Consistent with the previous report by Kim et al. (4), resistin mRNA was barely detected in normal, non-differentiating 3T3-L1 cells, and was markedly increased during differentiation (Fig. 3). The expression of fatty acid synthetase (FAS) was also upregulated (Fig. 3). In cells transfected with pDual GC-resistin, rat resistin mRNA and protein were expressed at higher levels throughout differentiation (Figs 3 and 4), although mouse resistin mRNA was barely detectable (data not shown). In addition, the differentiation process of rat resistin-overexpressing 3T3-L1 preadipocytes was significantly quickened. Compared with non-transfected 3T3-L1 cells, many more lipid droplets were visible in transfected cells prior to stimulation (day 0), and the degree of cellular contraction decreased after cells were stimulated with differentiation-inducing reagents. The transfected cells underwent extensive adipocyte conversion as judged by lipid staining using Oil Red O (Fig. 5). Consistent with the observed promotion of differentiation, the expression of several adipocyte differentiation markers such as CCAAT enhancer binding protein (C/EBPa), retinoid X receptor (RXRa) and lipoprotein lipase (LPL) was also upregulated at the onset of differentiation in rat resistin-transfected 3T3-L1 cells. Similarly, expression of preadipocyte factor-1 (Pref-1), an inhibitor of adipocyte differentiation, was downregulated, and the expression of glucose transporter-4 (GLUT4) remained relatively consistent (Fig. 6).

**Figure 3** Resistin and FAS mRNA expression during preadipocyte differentiation. PDual GC-resistin-transfected or non-transfected 3T3-L1 cells were induced to differentiate into adipocytes as above. Total RNA (1 μg) was reverse transcripted and an aliquot (10%) of the resulting cDNA was PCR amplified, electrophoresed in an ethidium bromide agarose gel and visualized under u.v. light. 1, day 0 of differentiation; 2, day 2 of differentiation; 3, day 4 of differentiation; 4, day 6 of differentiation; 5, day 8 of differentiation.

**Figure 4** Recombinant resistin is secreted mainly as a trimer. 3T3-L1 preadipocytes were transfected with pDual GC-resistin. Stably expressing lines were selected by G418 and differentiation was induced by treatment with MIX, insulin and DEX. Medium collected from these cells was electrophoresed on 12% SDS-PAGE gels and recombinant protein expression was detected by Western blotting with anti-His antibody. M, marker; 1, day 0 of differentiation; 2, day 2 of differentiation; 3, day 4 of differentiation; 4, day 6 of differentiation; 5, day 8 of differentiation.
Subcellular localization of resistin

As the Proscan program predicted the presence of a leucine zipper motif in the rat resistin protein, we next questioned whether resistin acts as a transcription factor to stimulate preadipocyte differentiation during adipocconversion. To address this, we investigated the subcellular localization of rat resistin-enhanced GFP (EGFP) prior to and during differentiation of resistin-transfected 3T3-L1 cells. We identified faint fluorescence in the cytoplasm at all time points before and during 3T3-L1 differentiation; most of the resistin was secreted into the cell culture medium (Fig. 7).

Resistin exists mainly as trimers

Resistin was believed to exist mainly as disulfide-linked homodimers (11), or to form dimers that then associated with each other to form tetramers, hexamers, octamers and so on (12). Our results indicate that, under our experimental conditions, exogenous resistin mainly exists as trimers, as determined by comparison to a standard molecular weight marker (Fig. 4). When sample loading was increased from 1 to 15 μg, we were able to detect monomeric, dimeric, tetrameric and pentameric resistin forms (Fig. 4).

siRNA inhibition of resistin expression inhibits preadipocyte differentiation

Contrary to the previous report by Kim et al. (4), we found that resistin promoted 3T3-L1 preadipocyte differentiation. To further verify our results, we inhibited resistin expression in 3T3-L1 cells via transfection of resistin-specific siRNA expression vectors. As shown in Fig. 8, the pSilencer 2.0-U6-resistin1 and pSilencer 2.0-U6-resistin3 vectors remarkably downregulated the expression of rat and mouse resistin at both the mRNA and protein levels, while no significant effects were detected in cells transfected with pSilencer 2.0-U6-resistin2. These results were consistent with the expression of FAS mRNA and the differentiation process of normal or resistin-transfected 3T3-L1 cells.

Discussion

Just as transgenic and knockout models allow researchers to study gene function in vivo, overexpression and RNA interference are powerful technologies for exploring gene function in mammalian cells. Recent studies in murine models have suggested that resistin may represent the long-sought link between obesity and insulin resistance (2, 3). Resistin was originally identified as a...
gene that is negatively regulated by several kinds of troglitazones (TZDs), insulin-sensitizing drugs, and is significantly upregulated during preadipocyte differentiation to mature adipocytes (3, 13). Resistin, which is mainly expressed in adipose tissue and is upregulated in several obese models, was thought to promote preadipocyte adipoconversion directly. However, unexpected reports indicated that both resistin and resistin-like molecule \(a\) (RELM\(a\)) inhibit adipocyte differentiation (4, 5). To address this apparent contradiction, we used \textit{in vitro} overexpression and RNA interference experiments to explore the effect of resistin on preadipocyte differentiation.

Compared with non-transfected 3T3-L1 cells, we found that pDual GC-resistin-transfected cells exhibited much more extensive adipocyte conversion. This promotion of adipocconversion was evident even at the very early stages of differentiation: small lipid droplets could be observed in transfected cells as early as day 0. This notable increase in adipoconversion was consistent throughout the whole process of differentiation.

To further confirm that resistin promotes adipocconversion, we generated short (21–23 nucleotide) synthetic double-strand siRNAs, which have been shown to induce significant, though transient, sequence-specific silencing effects (6, 7, 14). To prolong the effect, we synthesized three pairs of rat and mouse resistin mRNA-specific hairpin oligonucleotides and inserted them into the pSilencer 2.0-U6 siRNA expression vector. We found that transfection of pSilencer 2.0-U6-resistin\(_{1}\) and pSilencer 2.0-U6-resistin\(_{2}\) significantly downregulated resistin and FAS expression in both normal and resistin-transfected 3T3-L1 cells. These cells showed inhibition of the resistin-mediated increase in differentiation. However, adipoconversion in resistin-transfected cells remained greater than that observed in normal 3T3-L1 cells, suggesting that the silencing was incomplete. It is not clear why pSilencer 2.0-U6-resistin\(_{2}\) did not show significant silencing effects. The secondary structure of the target mRNA does not appear to have strong influence on silencing (9, 15), but it is possible that nearby regulatory protein binding sites could have interfered with binding of the siRNA or the RNA-induced silencing complex (RISC).

The mechanisms by which resistin regulates adipocyte differentiation are still unclear. Resistin is a secretory protein that is probably transported in the bloodstream, where it may interact with receptors on the surface of target cells such as hepatocytes and myocytes (2). However, the \textit{in vitro} experiments lack both bloodstream and target organs, suggesting that adipocytes may be direct targets of resistin. This could occur through one of two mechanisms: (1) the adipocyte cell membrane contains a receptor capable of binding autosecreted resistin and thereby triggering signal transduction cascades that promote preadipocyte differentiation; or (2) resistin, which contains a putative leucine zipper, acts as a transcription factor to regulate the expression of genes associated with energy metabolism or preadipocyte proliferation and differentiation. To investigate these hypotheses, we examined the subcellular localization of resistin by examining cells transfected with recombinant resistin-EGFP protein. We did not detect resistin in the nucleus of differentiating adipocytes and found that the majority of the protein was secreted. Thus, it seems more likely that the adipocytes may be able to respond to extracellular signaling from secreted, bound resistin. To provide further validation for this, normal 3T3-L1 cells were cultured in conditioned medium collected from cells stably expressing pDual GC-resistin. We observed an increase in differentiation under these conditions (data not shown), providing further evidence that secreted resistin increases adipocyte differentiation \textit{in vitro}.

![Figure 6](https://example.com/figure6.png)
Figure 7 Subcellular location of resistin before and after induction of differentiation in 3T3-L1 cells. The full-length coding region of the rat resistin gene was inserted into the pEGFP-N2 vector, and stably transfected into 3T3-L1 cells. Faint fluorescence was observed in the cytoplasm before and during 3T3-L1 differentiation. (A) pEGFP-N2 plasmid-transfected 3T3-L1 cells; (B) pEGFP-N2-resistin-transfected 3T3-L1 cells before differentiation; (C) pEGFP-N2-resistin-transfected 3T3-L1 cells, day 0 of differentiation; (D) pEGFP-N2-resistin-transfected 3T3-L1 cells, day 2 of differentiation.

Figure 8 Silencing of the resistin gene in non-transfected or rat resistin-transfected 3T3-L1 cells. A pair of reverse complementary cDNA fragments derived from the mouse GAPDH gene served as the positive control, while insert-free pSilencer 2.0-U6 vector served as the negative control. The concentration of GAPDH protein in normal and resistin-transfected 3T3-L1 cells was significantly decreased 48 h after transfection with the pSilencer 2.0-U6-GAPDH construct (C). Compared with the negative control, transfection with the pSilencer 2.0-U6-resistin1, and pSilencer 2.0-U6-resistin2 vectors downregulated rat and mouse resistin expression at both the mRNA and protein levels (A and B). In contrast, no significant effects were detected in cells transfected with the pSilencer 2.0-U6-resistin3 vector. These results were consistent with the expression of FAS mRNA. 1, day 0 of differentiation; 2, day 2 of differentiation; 3, day 4 of differentiation; 4, day 6 of differentiation; 5, day 8 of differentiation.
In summary, our data support the hypothesis that resistin stimulates preadipocyte differentiation. Thus, the protein may serve as a link between obesity and insulin resistance. Further studies will be needed to explore the regulation and function of resistin at the gene and protein levels, in the hope that a better understanding of this protein may lead to new therapies for diabetes mellitus 2.

References

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