**Gene Expression Signature in Adipose Tissue of Acromegaly Patients**

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**ABBREVIATED TITLE:** Analysis of Acromegalic Adipose Tissue

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**Abstract:**

Context: GH affects several molecular pathways regulating proliferation and metabolism. Determining the molecular changes associated with GH overproduction will help understand the normal and pathophysiological function of this hormone

Objective: To study tissue transcriptional changes induced by GH

Design: Prospective observational study from March 2011 to June 2012.

Setting: Tertiary referral center at the University of Michigan Pituitary clinic

Participants: Patients with acromegaly (n=9) or non functioning pituitary adenoma (n=11).

Intervention: The patients underwent clinical and metabolic profiling including assessment of HOMA-IR. Explants of adipose tissue were assayed ex-vivo for lipolysis. Adipose tissue was analysed by RNAseq.

Main Outcome: differences in adipose tissue mRNA expression between acromegaly patients and controls.

Results: Patients with acromegaly had a higher glucose, higher insulin levels and higher HOMA-IR score. We observed several previously reported transcriptional changes (*IGF1*, *IGFBP3*.*CISH, SOCS2)* that are classically known to be induced by GH in liver but are also induced in adipose tissue. We identified several novel transcriptional changes, some of which may be important for GH signal regulation (*PTPN3* and *PTPN4*) and the effect of GH on growth and proliferation. Several transcripts could potentially be important in GH-induced metabolic changes. Specifically, induction of *LPL*, *ABHD5*, *NRIP1* could contribute to enhanced lipolysis and may explain the enhancement of adipose tissue lipolysis in acromegaly patients. Higher expression of *TCF7L2* and the fatty acid desaturases *FADS1, FADS2* and *SCD* and could contribute to insulin resistance. Expression of *HSD11B1* was reduced and *GR* was increased, predicting modified glucocorticoid activity in acromegaly.

Conclusions: We identified the acromegaly gene expression signature in human adipose tissue. The significance of altered expression of specific transcripts will enhance our understanding of the metabolic and proliferative changes associated with acromegaly

**Introduction**

Acromegaly, excess growth hormone (GH) production secondary to a pituitary adenoma, is a rare condition with an annual incidence of 3 patients per million (1). The excess GH has important metabolic effects; the two most significant effects of GH on metabolism in adipose tissue are insulin resistance and lipolysis (2). Insulin resistance, presenting as diabetes or impaired glucose tolerance, is found in most acromegalic patients (3), and contributes to the enhanced morbidity (4).

There are not many studies addressing the effect of GH specifically on the subcutanous adipose tissue. Induction of STAT5 tyrosine phosphorylation and IGF1 mRNA expression has been detected in human subcutaneous adiopse tissue biopsies taken after acute GH treatment (5). Subcutaneous adipocytes extracted from acromegalic patients are insulin resistant *ex* vivo, and after a glucose tolerance test there was 50% less insulin binding to its receptor and markedly decreased insulin-related antilipolytic activity (6). *In vivo* measurement in humans detected GH-induced lipolysis in subcutanous adipose tissue (7). Pharmacologic inhibition of lipolysis reduced GH-induced insulin resistance, suggesting that some of this resistance is dependent on higher abundance of free fatty acids (8). Microarray of gene expression has been published for subcutanous adipose tissue biopsies before and after one year of GH treatment in GH deficient patients (9).

New techniques of transcriptomics open an opportunity to get a full picture of RNA expression in tissue and there is very little information on adipose tissue RNA expression in acromegaly patients. To study the effects of excess GH on adipose tissue, we used unbiased RNA sequencing to study adipose tissue from acromegaly patients and controls. We found a distinctive pattern of changes in many transcripts that are highly associated with acromegaly. Many of these alterations may contribute to the metabolic effect of GH and reveal novel mechanisms of GH-induced insulin resistance and lipolysis in adipose tissue.

Changes in cell ceramide and glucosylceramide have been also shown to be important *in vitro* and in obesity and glucocorticoid-induced insulin resistance (10–12). To assess whether ceramides are important in GH-induced insulin resistance we also measured ceramides in the same tissue samples.

**Materials and Methods**

**Patient recruitment**

The study was approved by the institutional review board of the University of Michigan Medical System. Written informed consent was obtained from all patients. Patients were recruited consecutively from those undergoing transsphenoidal adenomectomy at the University of Michigan Medical Center for acromegaly or non-functioning pituitary adenoma over a 12 month period. All but one patient were newly diagnosed, none had previous surgery and only the one previously diagnosed patient had a history of treatment with a somatostatin analog. Exclusion criteria were age <18, current hormone treatment including glucocorticoids, malignancy, inflammatory disease, diabetes type 1 and established pituitary hormone deficiencies. For each patient, a data sheet was completed including, age, sex, anthropometric measurements, diagnosis of hypertension, diabetes, results of blood tests and medications. Fasting blood samples were assayed for glucose (Siemens Advia 1800) and insulin (Life Technologies) as instructed by the manufacturers.

**Subcutaneous fat biopsy**

During the course of pituitary surgery a routine subcutaneous fat graft is utilized to seal the surgical field upon completion of the procedure. 500 mg of this fat graft was used for the study. ~200 mg were utilized for ex vivo lipolysis assay, ~300 mg was snap frozen in liquid nitrogen and stored at -80 degrees for RNA preparation and ceramide analysis.

***Ex vivo* lipolysis**

25 mg pieces of adipose tissue were pre-incubated for 15 minutes in KRBH buffer (sigma) at 37°C and then incubated for 1 hour at 37°C in 300 μl KRBH in the presence or absence of isoproterenol 30nM in duplicate. Glycerol was assayed in supernatants using a glycerol assay kit (sigma) as instructed by manufacturer.

**Ceramide Determinations**

Ceramide analysis of tissue samples was performed by liquid chromatography-triple quadrupole mass spectrometry (LC-QQQ) according to a modified version of the protocol reported in (13). Briefly, frozen tissue samples were pulverized under liquid nitrogen, then 20 mg portions were extracted using 1.6 mL of a 2:1:0.8 mixture of chloroform:methanol:water containing internal standards (50 ng each of C17 and C25 ceramide and C12 glucosylceramide per sample) (14). The organic layer of the extract was dried under nitrogen gas and reconstituted in 100 uL of 60:40 acetonitrile: isopropanol. The re-constituted extract was analyzed by electrospray ionization LC-MS/MS on an Agilent (Santa Clara, CA) 6410 triple quadrupole instrument operating in positive ion multiple reaction monitoring mode. The LC column used was a Waters (Milford, MA) Xbridge C18 2.5 µ, 50 mm x 2.1 mm i.d. Mobile phase A was 5mM ammonium acetate, adjusted to pH 9.9 with ammonium hydroxide; mobile phase B was 60:40 acetonitrile:isopropanol. The gradient consisted of a linear ramp from 50 to 100%B over 5 minutes, a 20 minute hold at 100%B, and re-equilibration at 50%B for 10 minutes. Injection volume was 25 µL. Ceramides and glucosylceramides were identified by retention time and by MS/MS fragmentation parameters, and were quantitated by peak area relative to the closest-matching internal standard using Agilent MassHunter Quantitative Analysis software.

**Transcriptomic Analysis**

Total RNA was extracted from adipose tissue using the RNEasy kit (Qiagen)and its quality was verified using the Agilent 2100 Bioanalyzer (Agilent Technologies). At the University of Michigan DNA Sequencing Core, cDNA libraries from polyA mRNA were prepared using TruSeq cDNA synthesis kit and sequenced using a HiSeq 2000 (Illumina). Samples were run on 2 lanes of a HiSeq 2000 (Illumina) generating 8 612 682 to 16 469 501 single-ended 50 bp reads per sample. These were aligned to the human genome (Enembl GRCh37.74, Genbank Assembly ID GCA\_000001405.14) using TopHat version 2.0.10 (15), Bowtie 2 version 2.1.0 (16) and Samtools version 0.1.18 . Reads were mapped to known genes using HTseq (17). Gene expression was analyzed using DESeq2 version 1.2.10 (18) . These subjects corresponded to the patients described in Table 1, with the exception of subjects 29 and 31 (both acromegaly patients), which had clinical data but no RNAseq data. These data are through the Gene Expression Omnibus (GSE57803).

For re-analysis of the dataset reported by Huo et al (19), we downloaded these data from the Gene Expression Omnibus (GSE2120) and compared the 48h treated control data to the 48h GH treated data. Analysis was performed using limma (version 3.18.7; (20)), with all p-values adjusted by the method of Benjamini-Hochberg (21).

**Statistics**

Descriptive statistics such as means and standard deviations were determined for clinical measurements. Student’s t-test was used to test the difference in means of these measurements between control and acromegaly patients. Normality assumption was checked by Shapiro-Wilk test. Wilcoxon rank sum test was performed for HOMA-IR score, insulin levels and the 14:0, 16:0, 20:0 ceramides and the C16:0 glucosylceramide species as these data were not normally distributed.

Welch’s t-test was used for basal lipolysis since the equal variance assumption was rejected by Levene's test (car package version 2.0-19 (22)). Correlation coefficients were calculated by Pearson's product-moment. Statistical significance in this study was defined as a p-value of less than 0.05. All statistical tests were performed using the R package (version 3.0.2,(23)). To correct for multiple hypotheses testing, p-values were adjusted by the method of Benjamini and Hochberg (21) and referred to in this manuscript as q-values.

We used Gene Set Enrichment Analysis (GSEA v2.0.13 (24,25)) to determine whether our rank-ordered gene list for the comparison of acromegaly vs control patients is enriched in genes from gene ontology, KEGG, transcription factor or microRNA target gene sets. The gene list was ranked based on log based 2 fold change and the statistical significance of the enrichment score was determined by performing 1000 phenotype permutation. Other settings for GSEA preranked were left by the software default. To test for enrichment of genes identified in the Huo *et al.* dataset (19), we used Fisher’s exact test..

**Results and Discussion**

**Patient characteristics**

Clinical and metabolic measurements were obtained for 9 acromegaly patients and 11 controls. Patient characteristics are shown in Table 1. There was no statistically significant difference in body mass index (BMI), abdominal circumference or weight. Acromegaly patients were younger (p=0.011) and taller than their controls (p=0.036).

**Acromegaly patients were more insulin resistant and had higher lipolysis**

Acromegaly patients had elevated fasting glucose levels (p=0.013) and higher fasted insulin (p=0.012, Figure 1A-B). When combined, we observed higher HOMA-IR scores in the acromegalic patients than in the controls (p=0.001, Figure 1C), reflecting a significant decrease in insulin sensitivity in the acromegaly patients, consistent with previous clinical findings (3).

Subcutaneous adipose tissue chunks for lipolysis assay were available from 6 acromegaly patients and 9 controls. As expected by previous data on GH and lipolysis, the results suggested that acromegaly patients may have higher basal lipolysis (p=0.11), and higher lipolysis in the presence of isoproterenol (p=0.058) even though they did not achieve statistical significance (Figure 1D). These data are consistent with previous reports linking GH signaling with increased lipolysis (26).

**Transcriptomic Analysis**

To determine which genes are altered in adipose tissue in acromegaly subjects, we performed a transcriptomic analysis of subcutaneous adipose tissue mRNA from 7 acromegalic patients and 11 controls. We identified 671 genes that had significantly different expression in acromegaly, of these 241 genes were down-regulated and 431 were up-regulated in adipose tissue from the acromegalic patients. These transcripts form a signature identifying transcriptional differences in adipose tissue in response to long-term exposure to GH (Figure 2 and Supplementary Table 1).

Gene set enrichment analysis testing KEGG pathways (27,28) showed enrichment of genes in the categories involved in metabolism, including fatty acid metabolism, biosynthesis of unsaturated fatty acids, valine leucine and isoleucine degradation, propanoate metabolism and citrate cycle (Supplementary Tables 2 and 3). We also examined the transcription factor networks that may underlie these changes in mRNA levels. We identified an up-regulation of several candidate transcription factors and microRNA’s (Supplementary Table 4) whose targets are significantly altered in acromegalic white adipose tissue. Notably among these are an up-regulation of GATA-1 and FOXO4 targets and a down-regulation of PPAR, NF-κB and SRF responsive genes.

Previous work by Huo *et al*. (19) examined an analogous *in vitro* system, where 3T3-F442A adipocytes were treated with GH for a variety of time points. The longest time point (48h) is potentially analogous to the chronic GH exposure that occurs in adipose tissue from acromegaly patients. We re-analyzed that data set, looking at only the 48h GH treatment time point. In our dataset we found 560 significantly different acromegaly genes out of a total of 22810 genes tested (or 2.5%). Out of these 560 genes, 266 have mouse homologs, and 310 probes in the Huo *et al* dataset. From these probes, 32 were significantly different in both datasets (or 9.3%). Therefore the genes from the acromegaly dataset are enriched in the growth hormone treated dataset (p=7.8 × 10-5). The genes that were significantly different in both datasets were *Bst1, Capn6, Ccng1, Cish, Elovl5, Fads1, Fasn, Fmo1, Gdf5, Ggct, Hmgcs1, Igf1, Igfbp3, Itpr2, Klf4, Mpdz, Phldb2, Pkd2, Pld1, Prlr, Pten, Ptger3, Rpa3, Scd2, Scp2, Sept4, Socs2, Wisp2* and *Wnt11.*

**Established GH responsive genes are up-regulated in adipose tissue from acromegaly patients**

Since acromegaly is caused by an overproduction of GH, we first analyzed known GH responsive genes. We found that expression of previously reported GH responsive genes, including *IGF1* (3 fold, q<10-5), and *IGFBP3* (2.3 fold, q<10-5) are elevated in acromegalic patients (Figure 3A). IGF-1 has been shown to be induced in adipocytes exposed to GH (29), while there were no previous reports regarding IGF-BP3 induction in adipose tissue. The confirmation of these previously reported acromegaly or GH dependent transcriptional changes strengthens our interpretation of other transcriptional changes. Neither the growth hormone receptor (GHR) nor the IGF-1 receptor (*IGF1R)* was significantly altered in acromegalic adipose tissue.

There was a correlation between *IGF1* mRNA and levels of IGF-1 in serum in the acromegaly patients (R2=0.51, p=0.043; Figure 3C), reflecting that increased induction of *IGF1* in adipose tissue is similar in its extent to serum IGF1 induction. Serum IGF1 is primarily thought to be derived from liver tissue (30). Our data demonstrates that expression of the adipose tissue *IGF1* gene correlates well with that of serum IGF-1, suggesting that adipose tissue may also be a source of IGF-1 in acromegalic subjects.

**A novel negative feedback loop is induced by chronic exposure to high GH levels**

*SOCS2* AND *CISH,* both suppressors of cytokine signaling that have been shown to be important in down-regulating GH signaling, are up-regulated in acromegaly (1.7 and 3.3 fold respectively (q<0.0015 and q<10-5, Figure 3C). These have been shown to be induced in liver and muscle by GH (31), and SOCS2 has also been reported to be induced in adipocytes by GH (19,29).

Among signaling pathways, MAP kinase signaling, insulin signaling (see below) and JAK-STAT signaling were down-regulated in the acromegaly patients including lower expression of ERK1 (*MAPK3*) and ERK5 (*MAPK7*) and a 4 fold lower expression of their downstream transcription factors *FOS, JUN, JUNB* (all three are ~2 fold lower in acromegaly patients, q<0.02, Supplementary Table 2 and Supplementary Figure 1A).

We observed induction of the tyrosine phosphatases, *PTPN3* (also called PTP-H1, 2.2 fold higher q<0.001) and *PTPN4* (1.6 fold higher, q<10-4) in acromegaly (Figure 3D). *PTPN3* has been reported to bind GH receptor *in vitro* in the presence of GH (32), and its overexpression reduces STAT5 signaling in response to GH (33). *Ptpn3* Knockout mice have excessive GH activity, as demonstrated by excessive growth accompanied by a strong induction of liver *IGF1* mRNA and serum IGF-1 (33). This is the first report of enhanced abundance of PTPN3 mRNA in response to GH exposure. The increased expression of *PTPN3* that we have observed in acromegaly suggests that this may be an additional negative feedback pathway induced by GH and reducing GH signaling.

**Genes controlling DNA replication, proliferation and apoptosis**

We observed a difference in expression of several different genes regulating cellular proliferation in acromegalic subjects. Broadly the KEGG category containing DNA replication was enriched in acromegalic white adipose tissue, (Supplementary Table 2). In addition to this, expression of Cyclin C (*CCNC;* 1.23 fold q<0.01), Cyclin E (*CCNE1;* 2.5 fold q<10-4*)*, which are important for transition from G1 to S, were increased in acromegalic patients, and the negative regulator, cyclin dependent kinase inhibitor B (*CDKN2B*) was decreased (0.6 fold q<0.01, Supplementary Figures 1B). Notably, *CDKN2B* is also a diabetes susceptibility gene identified repeatedly in GWAS studies (34,35).

Additional DNA replication genes that were induced were nucleosome assembly protein 1-like 1 (*NAP1L1,* 1.3 fold q<0.02) and origin recognition complex, subunit 2(*ORC2*, 1.6 fold q<0.002), which are important for DNA replication, and the antiapoptotic regulators *BAG4*(BCL2-associated athanogene 4. 1.7 fold q<10-4) and *CAPN6* (calpain 6, 2.4 fold q<0.001) were also induced (Supplementary Figures 1C). Together these implicate increased cell division, potentially of immune, vascular or pre-adipocyte cells in adipose tissue depots.

Apoptosis signal-regulating kinase 1 (*MAP3K5*) expression is higher in acromegaly (1.3 fold q<0.02), and there is also higher expression of its downstream substrates p38α (*MAPK14* 1.2 fold q<0.005), p38*δ*  (*MAPK13*, 2.3 fold q<10-4) and *MAPKAPK3* (1.4 fold q<0.03, Supplementary Figure 1D). The pathway is thought to regulate apoptosis in response to stress. The effect of GH on these transcripts has not been reported before, and they could account for the effects of enhanced cell proliferation and apoptosis in response to GH (36).

**Transcriptional changes regulating lipid metabolism and localization that may contribute to enhanced lipolysis**

To determine the potential causes of the increased lipolysis observed in Figure 1D, we examined the expression of human lipases in these adipose tissues. We observed no significant difference in expression of the three classical triglyceride lipolysis enzymes hormone sensitive lipase (*LIPE*), adipose triglyceride lipase (*PNPLA*) or monoglycerol lipase (*MGLL*; Figure 4A). Lipoprotein lipase (*LPL*), the lipase important for lipolysis of triglycerides in apolipoproteins, was significantly more highly expressed in acromegaly patients (1.9 fold, q<10 -3, Figure 4A). A strong induction of LPL expression in response to GH and absence of change in HSL was demonstrated before in a preadipocyte cell line (37–39) and in adipose tissue biopsies from GH deficient patients after treatment with GH (9). Notably, studies that addressed LPL enzymatic activity and not expression have found either no change or even a reduction in LPL activity in response to GH treatment of human adipocytes *in vitro* (40,41).

Although neither Hormone Sensitive Lipase (*LIPE*) nor ATGL (*PNPLA2*) were altered, two direct regulators of HSL and ATGL activity in adipocytes, abhydrolase domain containing 5 (*ABHD5*, also called CGI58 (42)), and nuclear receptor interacting protein 1 (*NRIP* (also called RIP140 (43)) were expressed at higher levels in adipose tissue from acromegaly patients (2.1 fold q<10-3 and 1.6 fold, q<0.03 Figure 4B). CGI58 is an allosteric activator of lipolytic activity and RIP140 regulates it's activity, therefore these data suggest that their transcriptional up-regulation could contribute to the induction of lipolysis by GH. NRIP1 has also been proposed to be a transcription regulator of genes involved in lipid and glucose metabolism (43) and its induction could contribute to additional metabolic effects of GH including disrupted glucose metabolism.

We next examined the expression of G-protein coupled receptors that induce lipolysis. The β3 adrenergic (*ADRB3*) was more highly expressed in acromegaly patients compared to the controls (2.9 fold, q< 0.002). The 1 receptor was also more highly expressed in acromegalic adipose tissue though it did not reach statistical significance (1.4 fold, q=0.14; Figure 4B) suggesting a potential sensitization of these patients to adrenergic stimuli. The Calcitonin receptor like (*CALCRL*), which can function as either an adrenomedullin or CGRP receptor subunit, is higher in acromegaly (1.5 fold, q<0.05, Figure 4B). Activation of these receptors also activates cAMP-dependent lipolysis and may contribute to enhanced lipolysis in these patients (44–46).

Angiopoietin like 4 (*ANGPTL4*), which has been recently shown to be induced in muscle in response to acute GH treatment, and suggested as a possible regulator of lipolysis (31) was not observed to have significantly different expression between the acromegaly patients and the controls (q=0.77).

In contrast to the lipolytic phenotype of acromegalic patients, several fatty acid synthesis genes were expressed at significantly higher levels in acromegaly patients (Figure 4C). These include *ACSS2* (1.5 fold, q<0.03) and *ACSS3* (1.5 fold, q<0.03) which catalyze the activation of acetate for use in lipid synthesis . We also observed elevations in Acetoacetyl Co-A synthase (*AACS;* 1.75 fold, q<0.05), Acetyl Co-A carboxylse (*ACACA*, 1.62 q<0.02), and Acyl-CoA synthetase long-chain family member 3 *ACSL3* (1.3 fold, q<0.03)*,* whichconvert long-chain fatty acids into fatty acyl-CoA esters. Finally we observed an elevation in fatty acid synthase *FASN* (2.2 fold, q<0.02) in the acromegaly patients. By pathway analysis, both fatty acid metabolism and unsaturated fatty acid biosynthetic pathways were up-regulated in the acromegaly patients (see Supplementary Table 2 and below). This up-regulation may represent compensation by the adipose tissue due to enhanced lipid breakdown and oxidation in this and other tissues in acromegaly patients.

With respect to glycogen metabolism, expression of *UGP2* (1.4 fold, q<0.02) and expression of muscle glycogen phosphorylase (*PYGM*) (2.3 fold, q<0.0002) were higher in the acromegaly patients (Supplementary Figure 1E). The significance of glycogen in adipose tissue, or changes in glycogen content in acromegalic adipose tissue have not been characterized, but these findings would predict that the rates of glycogenolysis in acromegalic white adipose tissue would be elevated.

**Transcripts altered in acromegaly that may contribute to insulin resistance**

One of the most pronounced differences between the acromegaly patients and the controls was a ~3 fold higher expression (q<1x10-5, Figure 4D) in expression of the three fatty acid desaturases - stearoyl-CoA desaturase (*SCD*, delta-9-desaturase), fatty acid desturase 1 (*FADS1*, delta-5-desaturase) and fatty acid desturase 2 (*FADS2*, delta-6-desaturase). Cytochrome b5 type A (*CYB5A)*, an activator of SCD, is also induced (1.7 fold, q=0.001). *SCD* products and *FADS2* mRNA have recently been shown to be induced by GH in mice (47) The change in expression of these enzymes could be a possible link between acromegaly and insulin resistance do to an elevation of unsaturated fatty acids, as activity of *FADS1* and *FADS2* are associated with metabolic syndrome (48,49).

We observed no decrease in expression of canonical transcripts important for insulin signaling and response to insulin in adipocytes, including insulin receptor (*INSR*), *IRS1, IRS2*, *AKT1-3*, or GLUT4 (*SLC2A4* ; see Supplementary Figure 2A). This indicates that the observed insulin resistance is not caused by mRNA decreases in these genes. In fact, the KEGG category containing insulin signaling genes was generally up-regulated in these tissues (Supplementary Table 2). AKT1 was significantly higher (1.3 fold, q<0.002) and the remainder of these genes trended to be more highly expressed in the adipose tissue from the acromegalic and insulin resistant patients, potentially underlying a transcriptional up-regulation that compensates for an alternative insulin resistance mechanism.

One previously identified candidate is the phosphoinositide-3-kinase, regulatory subunit 1 (*PIK3R1*, also called p85α), which was induced by GH in mouse adipose tissue and thought to contribute to GH-induced insulin resistance (50). In our study it's expression was not different in the acromegaly patients (q=0.95).

The cytokine modulators *STAT6* and the pro-inflammatory protein kinase IKKβ (*IKBKB*) are expressed at lower levels (Supplementary Table B). Furthermore, the pro-inflammatory cytokines *IL1B*, *IL6* and *MCP1* and the pro-inflammatory protein kinase *IKBKE* all trend towards lower expression, and genes from several KEGG pathways involved in inflammation were expressed at lower levels in the acromegaly cohort (Supplementary Table 2 and Supplementary Figure 2B). These data support the hypothesis that insulin resistance in these patients is not due to enhanced inflammatory signaling.

To test biochemically whether ceramides may play a role in the acromegaly associated insulin resistance, we took a lipidomics approach to analyze ceramide and glucosylceramide species from the adipose tissue explants of these patients. Elevated ceramides have been proposed to mediate insulin resistance by several models (10–12,51). We observed a modest down-regulation of the mRNA levels of glycosylsphingolipid metabolic genes in our data (normalized enrichment score = -0.86 q=0.71). We then measured ceramide species from 7 acromegaly patients and 11 control patients directly and observed no statistically significant changes in any ceramide species (Supplementary Figure 3, q-values all >0.25). We did however, detect modest elevations of C16:0, C18:0 and C24:0 ceramide species in WAT from acromegalic patients. We therefore do not have strong evidence to support the hypothesis that ceramide elevations are causative of insulin resistance in acromegalic white adipose tissue.

*TCF7L2*, a transcription factor regulating many metabolism genes as well as a diabetes susceptibility gene (52) is up-regulated in the acromegaly patients (1.5 fold, q<0.0002, Figure 4E). Mice with liver specific knockout of *Tcf7l2* are hypoglycemic, while transgenic mice overexpressing liver *Tcf7l2* are hyperglycemic (53). *TCF7L2* in subcutaneous fat is higher and expression of splice isoforms is reduced in subcutaneous fat and in liver following bariatric surgery (54). Higher expression of TCF7L2 could also therefore be linked to insulin resistance in acromegaly.

**Glucocorticoid regulation**

11βHydroxysteroid dehydrogenase 1 (*HSD11B1*), the enzyme that activates cortisone to cortisol, was reduced 4 fold in acromegaly patients (q<0.002. Figure 2F). The down-regulation of expression and activity of this enzyme by GH/IGF1 has been confirmed both *in vitro* (55), in GH deficient patients treated with GH (56) and in acromegaly patients (57,58). In addition, we found higher expression of the glucocorticoid receptor (*NR3C1,*1.5 fold q<10-5) and the mineralocorticoid receptor (*NR3C2*, 1.3 fold q<0.05) in acromegaly patients (Figure 2F). Glucocorticoid receptor expression is repressed by cortisol (59), so the higher expression may be due to the reduced local cortisol levels caused by lowered *HSD11B1*.

**Summary**

In this study we have described a transcriptional signature in adipose tissue from subjects with acromegaly. We identified 671 adipose tissue genes altered in acromegaly. Some of these genes may be direct targets of increased GH or IGF-1 signaling in adipose tissue, whereas others may be secondary adaptations to this condition.

The fact that the patients consistently had a relatively uniform change of expression of these genes suggests that we are able to draw valid conclusions about adipose tissue in acromegalic patients even from this small cohort. Furthermore, as mentioned throughout, our data agrees with several previous studies in animal models and patients. The confirmation of these previously reported GH-dependent transcriptional changes strengthens our interpretation of other transcriptional changes.

These data provide a variety of novel transcriptional changes that may be causative of the co-morbidities associated with acromegaly. Further studies in animals and cells using knockout or overexpression of specific transcripts may verify which of the changes is crucial in metabolic effects of GH in adipose tissue.

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**References**

1. **Holdaway IM, Rajasoorya C.** Epidemiology of acromegaly. *Pituitary*. 1999;2(1):29–41.

2. **Vijayakumar A, Novosyadlyy R, Wu Y, Yakar S, LeRoith D.** Biological effects of growth hormone on carbohydrate and lipid metabolism. *Growth Horm IGF Res*. 2010;20(1):1–7.

3. **Ezzat S, Forster MJ, Berchtold P, Redelmeier DA, Boerlin V, Harris AG.** Acromegaly. Clinical and biochemical features in 500 patients. *Medicine (Baltimore)*. 1994;73(5):233–40.

4. **Colao A, Baldelli R, Marzullo P, Ferretti E, Ferone D, Gargiulo P, Petretta M, Tamburrano G, Lombardi G, Liuzzi A.** Systemic hypertension and impaired glucose tolerance are independently correlated to the severity of the acromegalic cardiomyopathy. *J Clin Endocrinol Metab*. 2000;85(1):193–9.

5. **Jørgensen JOL, Jessen N, Pedersen SB, Vestergaard E, Gormsen L, Lund SA, Billestrup N.** GH receptor signaling in skeletal muscle and adipose tissue in human subjects following exposure to an intravenous GH bolus. *Am J Physiol Endocrinol Metab*. 2006;291(5):E899–905.

6. **Bolinder J, Ostman J, Werner S, Arner P.** Insulin action in human adipose tissue in acromegaly. *J Clin Invest*. 1986;77(4):1201–6.

7. **Gravhølt CH, Schmitz O, Simonsen L, Bülow J, Christiansen JS, Møller N.** Effects of a physiological GH pulse on interstitial glycerol in abdominal and femoral adipose tissue. *Am J Physiol*. 1999;277(5 Pt 1):E848–54.

8. **Nielsen S, Møller N, Christiansen JS, Jørgensen JO.** Pharmacological antilipolysis restores insulin sensitivity during growth hormone exposure. *Diabetes*. 2001;50(10):2301–8.

9. **Khalfallah Y, Sassolas G, Borson-Chazot F, Vega N, Vidal H.** Expression of insulin target genes in skeletal muscle and adipose tissue in adult patients with growth hormone deficiency: effect of one year recombinant human growth hormone therapy. *J Endocrinol*. 2001;171(2):285–92.

10. **Adams JM, Pratipanawatr T, Berria R, Wang E, DeFronzo RA, Sullards MC, Mandarino LJ.** Ceramide content is increased in skeletal muscle from obese insulin-resistant humans. *Diabetes*. 2004;53(1):25–31.

11. **Aerts JM, Ottenhoff R, Powlson AS, Grefhorst A, van Eijk M, Dubbelhuis PF, Aten J, Kuipers F, Serlie MJ, Wennekes T, Sethi JK, O’Rahilly S, Overkleeft HS.** Pharmacological inhibition of glucosylceramide synthase enhances insulin sensitivity. *Diabetes*. 2007;56(5):1341–9.

12. **Holland WL, Brozinick JT, Wang L-P, Hawkins ED, Sargent KM, Liu Y, Narra K, Hoehn KL, Knotts TA, Siesky A, Nelson DH, Karathanasis SK, Fontenot GK, Birnbaum MJ, Summers SA.** Inhibition of ceramide synthesis ameliorates glucocorticoid-, saturated-fat-, and obesity-induced insulin resistance. *Cell Metab*. 2007;5(3):167–79.

13. **Kasumov T, Huang H, Chung Y-M, Zhang R, McCullough AJ, Kirwan JP.** Quantification of ceramide species in biological samples by liquid chromatography electrospray ionization tandem mass spectrometry. *Anal Biochem*. 2010;401(1):154–61.

14. **Bligh EG, Dyer WJ.** A rapid method of total lipid extraction and purification. *Can J Biochem Physiol*. 1959;37(8):911–7.

15. **Kim D, Pertea G, Trapnell C, Pimentel H, Kelley R, Salzberg SL.** TopHat2: accurate alignment of transcriptomes in the presence of insertions, deletions and gene fusions. *Genome Biol*. 2013;14(4):R36.

16. **Langmead B, Trapnell C, Pop M, Salzberg SL.** Ultrafast and memory-efficient alignment of short DNA sequences to the human genome. *Genome Biol*. 2009;10(3):R25.

17. **Anders S, Pyl PT, Huber W.** HTSeq – A Python framework to work with high-throughput sequencing data. 2014:1–5.

18. **Love MI, Huber W, Anders S.** *Moderated estimation of fold change and dispersion for RNA-Seq data with DESeq2*.; 2014. doi:10.1101/002832.

19. **Huo JS, McEachin RC, Cui TX, Duggal NK, Hai T, States DJ, Schwartz J.** Profiles of growth hormone (GH)-regulated genes reveal time-dependent responses and identify a mechanism for regulation of activating transcription factor 3 by GH. *J Biol Chem*. 2006;281(7):4132–41.

20. **Smyth GK.** Limma: linear models for microarray data. In: Gentleman R, Carey V, Dudoit S, Irizarry R, Huber W, eds. *Bioinformatics and Computational Biology Solutions Using R and Bioconductor*. New York: Springer; 2005:397–420.

21. **Benjamini Y, Hochberg Y.** Controlling the False Discovery Rate: A Practical and Powerful Approach to Multiple Testing. *J R Stat Soc Ser B*. 1995;57(1):289–300.

22. **Fox J, Weisberg S.** *An {R} Companion to Applied Regression*. Second. Thousand Oaks {CA}: Sage; 2011.

23. **R Development Core Team, R Core Team.** R: A language and environment for statistical computing. 2011.

24. **Mootha VK, Lindgren CM, Eriksson K-F, Subramanian A, Sihag S, Lehar J, Puigserver P, Carlsson E, Ridderstråle M, Laurila E, Houstis N, Daly MJ, Patterson N, Mesirov JP, Golub TR, Tamayo P, Spiegelman B, Lander ES, Hirschhorn JN, Altshuler D, Groop LC.** PGC-1alpha-responsive genes involved in oxidative phosphorylation are coordinately downregulated in human diabetes. *Nat Genet*. 2003;34(3):267–73.

25. **Subramanian A, Tamayo P, Mootha VK, Mukherjee S, Ebert BL, Gillette MA, Paulovich A, Pomeroy SL, Golub TR, Lander ES, Mesirov JP.** Gene set enrichment analysis: a knowledge-based approach for interpreting genome-wide expression profiles. *Proc Natl Acad Sci U S A*. 2005;102(43):15545–50.

26. **Moller L, Norrelund H, Jessen N, Flyvbjerg A, Pedersen SB, Gaylinn BD, Liu J, Thorner MO, Moller N, Lunde Jorgensen JO.** Impact of growth hormone receptor blockade on substrate metabolism during fasting in healthy subjects. *J Clin Endocrinol Metab*. 2009;94(11):4524–32.

27. **Ashburner M, Ball CA, Blake JA, Botstein D, Butler H, Cherry JM, Davis AP, Dolinski K, Dwight SS, Eppig JT, Harris MA, Hill DP, Issel-Tarver L, Kasarskis A, Lewis S, Matese JC, Richardson JE, Ringwald M, Rubin GM, Sherlock G.** Gene ontology: tool for the unification of biology. The Gene Ontology Consortium. *Nat Genet*. 2000;25(1):25–9.

28. **Young MD, Wakefield MJ, Smyth GK, Oshlack A.** Gene ontology analysis for RNA-seq: accounting for selection bias. *Genome Biol*. 2010;11(2):R14.

29. **Fleenor D, Arumugam R, Freemark M.** Growth hormone and prolactin receptors in adipogenesis: STAT-5 activation, suppressors of cytokine signaling, and regulation of insulin-like growth factor I. *Horm Res*. 2006;66(3):101–10.

30. **Haluzik M, Yakar S, Gavrilova O, Setser J, Boisclair Y, LeRoith D.** Insulin resistance in the liver-specific IGF-1 gene-deleted mouse is abrogated by deletion of the acid-labile subunit of the IGF-binding protein-3 complex: relative roles of growth hormone and IGF-1 in insulin resistance. *Diabetes*. 2003;52(10):2483–9.

31. **Clasen BFF, Krusenstjerna-Hafstrøm T, Vendelbo MH, Thorsen K, Escande C, Møller N, Pedersen SB, Jørgensen JOL, Jessen N.** Gene expression in skeletal muscle after an acute intravenous GH bolus in human subjects: identification of a mechanism regulating ANGPTL4. *J Lipid Res*. 2013;54(7):1988–97.

32. **Pasquali C, Curchod M-L, Wälchli S, Espanel X, Guerrier M, Arigoni F, Strous G, Hooft van Huijsduijnen R.** Identification of protein tyrosine phosphatases with specificity for the ligand-activated growth hormone receptor. *Mol Endocrinol*. 2003;17(11):2228–39.

33. **Pilecka I, Patrignani C, Pescini R, Curchod M-L, Perrin D, Xue Y, Yasenchak J, Clark A, Magnone MC, Zaratin P, Valenzuela D, Rommel C, Hooft van Huijsduijnen R.** Protein-tyrosine phosphatase H1 controls growth hormone receptor signaling and systemic growth. *J Biol Chem*. 2007;282(48):35405–15.

34. **Sladek R, Rocheleau G, Rung J, Dina C, Shen L, Serre D, Boutin P, Vincent D, Belisle A, Hadjadj S, Balkau B, Heude B, Charpentier G, Hudson TJ, Montpetit A, Pshezhetsky A V, Prentki M, Posner BI, Balding DJ, Meyre D, Polychronakos C, Froguel P.** A genome-wide association study identifies novel risk loci for type 2 diabetes. *Nature*. 2007;445(7130):881–5.

35. **Saxena R, Voight BF, Lyssenko V, Burtt NP, de Bakker PIW, Chen H, Roix JJ, Kathiresan S, Hirschhorn JN, Daly MJ, Hughes TE, Groop L, Altshuler D, Almgren P, Florez JC, Meyer J, Ardlie K, Bengtsson Boström K, Isomaa B, Lettre G, Lindblad U, Lyon HN, Melander O, Newton-Cheh C, Nilsson P, Orho-Melander M, Råstam L, Speliotes EK, Taskinen M-R, Tuomi T, Guiducci C, Berglund A, Carlson J, Gianniny L, Hackett R, Hall L, Holmkvist J, Laurila E, Sjögren M, Sterner M, Surti A, Svensson M, Svensson M, Tewhey R, Blumenstiel B, Parkin M, Defelice M, Barry R, Brodeur W, Camarata J, Chia N, Fava M, Gibbons J, Handsaker B, Healy C, Nguyen K, Gates C, Sougnez C, Gage D, Nizzari M, Gabriel SB, Chirn G-W, Ma Q, Parikh H, Richardson D, Ricke D, Purcell S.** Genome-wide association analysis identifies loci for type 2 diabetes and triglyceride levels. *Science*. 2007;316(5829):1331–6.

36. **Waters MJ, Brooks AJ.** Growth hormone and cell growth. *Endocr Dev*. 2012;23:86–95.

37. **Pradines-Figueres A, Barcellini-Couget S, Dani C, Baudoin C, Ailhaud G.** Inhibition by serum components of the expression of lipoprotein lipase gene upon stimulation by growth hormone. *Biochem Biophys Res Commun*. 1990;166(3):1118–25.

38. **Barcellini-Couget S, Vassaux G, Negrel R, Ailhaud G.** Rise in cytosolic Ca2+ abolishes in preadipose cells the expression of lipoprotein lipase stimulated by growth hormone. *Biochem Biophys Res Commun*. 1994;199(1):136–43.

39. **Padines-Figuères A, Barcellini-Couget S, Dani C, Vannier C, Ailhaud G.** Transcriptional control of the expression of lipoprotein lipase gene by growth hormone in preadipocyte Ob1771 cells. *J Lipid Res*. 1990;31(7):1283–91.

40. **Simsolo RB.** Effects of acromegaly treatment and growth hormone on adipose tissue lipoprotein lipase. *J Clin Endocrinol Metab*. 1995;80(11):3233–3238.

41. **Richelsen B, Pedersen SB, Kristensen K, Børglum JD, Nørrelund H, Christiansen JS, Jørgensen JOL.** Regulation of Lipoprotein Lipase and Hormone-Sensitive Lipase Activity and Gene Expression in Adipose and Muscle Tissue by Growth Hormone Treatment During Weight Loss in Obese Patients. 2000;49(7):906–911.

42. **Lass A, Zimmermann R, Haemmerle G, Riederer M, Schoiswohl G, Schweiger M, Kienesberger P, Strauss JG, Gorkiewicz G, Zechner R.** Adipose triglyceride lipase-mediated lipolysis of cellular fat stores is activated by CGI-58 and defective in Chanarin-Dorfman Syndrome. *Cell Metab*. 2006;3(5):309–19.

43. **Ho P-C, Chuang Y-S, Hung C-H, Wei L-N.** Cytoplasmic receptor-interacting protein 140 (RIP140) interacts with perilipin to regulate lipolysis. *Cell Signal*. 2011;23(8):1396–403.

44. **Linscheid P, Seboek D, Zulewski H, Keller U, Müller B.** Autocrine/paracrine role of inflammation-mediated calcitonin gene-related peptide and adrenomedullin expression in human adipose tissue. *Endocrinology*. 2005;146(6):2699–708.

45. **Iemura-Inaba C, Nishikimi T, Akimoto K, Yoshihara F, Minamino N, Matsuoka H.** Role of adrenomedullin system in lipid metabolism and its signaling mechanism in cultured adipocytes. *Am J Physiol Regul Integr Comp Physiol*. 2008;295(5):R1376–84.

46. **Go AGG, Chow KHM, Hwang ISS, Tang F.** Adrenomedullin and its receptor components in adipose tissues: Differences between white and brown fats and the effects of adrenergic stimulation. *Peptides*. 2007;28(4):920–7.

47. **Oberbauer AM, German JB, Murray JD.** Growth hormone enhances arachidonic acid metabolites in a growth hormone transgenic mouse. *Lipids*. 2011;46(6):495–504.

48. **Kröger J, Schulze MB.** Recent insights into the relation of Δ5 desaturase and Δ6 desaturase activity to the development of type 2 diabetes. *Curr Opin Lipidol*. 2012;23(1):4–10.

49. **Mayneris-Perxachs J, Guerendiain M, Castellote AI, Estruch R, Covas MI, Fitó M, Salas-Salvadó J, Martínez-González MA, Aros F, Lamuela-Raventós RM, López-Sabater MC.** Plasma fatty acid composition, estimated desaturase activities, and their relation with the metabolic syndrome in a population at high risk of cardiovascular disease. *Clin Nutr*. 2013;33(1):90–7.

50. **Del Rincon J-P, Iida K, Gaylinn BD, McCurdy CE, Leitner JW, Barbour LA, Kopchick JJ, Friedman JE, Draznin B, Thorner MO.** Growth hormone regulation of p85alpha expression and phosphoinositide 3-kinase activity in adipose tissue: mechanism for growth hormone-mediated insulin resistance. *Diabetes*. 2007;56(6):1638–46.

51. **Chavez JA, Knotts T a, Wang L-P, Li G, Dobrowsky RT, Florant GL, Summers S a.** A role for ceramide, but not diacylglycerol, in the antagonism of insulin signal transduction by saturated fatty acids. *J Biol Chem*. 2003;278(12):10297–303.

52. **Ip W, Chiang Y-TA, Jin T.** The involvement of the wnt signaling pathway and TCF7L2 in diabetes mellitus: The current understanding, dispute, and perspective. *Cell Biosci*. 2012;2(1):28.

53. **Boj SF, van Es JH, Huch M, Li VSW, José A, Hatzis P, Mokry M, Haegebarth A, van den Born M, Chambon P, Voshol P, Dor Y, Cuppen E, Fillat C, Clevers H.** Diabetes risk gene and Wnt effector Tcf7l2/TCF4 controls hepatic response to perinatal and adult metabolic demand. *Cell*. 2012;151(7):1595–607.

54. **Hindle AK, Brody F, Tevar R, Kluk B, Hill S, McCaffrey T, Fu S.** TCF7L2 expression in diabetic patients undergoing bariatric surgery. *Surg Endosc*. 2009;23(4):700–4.

55. **Napolitano a, Voice MW, Edwards CR, Seckl JR, Chapman KE.** 11Beta-hydroxysteroid dehydrogenase 1 in adipocytes: expression is differentiation-dependent and hormonally regulated. *J Steroid Biochem Mol Biol*. 1998;64(5-6):251–60.

56. **Paulsen SK, Pedersen SB, Jørgensen JOL, Fisker S, Christiansen JS, Flyvbjerg A, Richelsen B.** Growth hormone (GH) substitution in GH-deficient patients inhibits 11beta-hydroxysteroid dehydrogenase type 1 messenger ribonucleic acid expression in adipose tissue. *J Clin Endocrinol Metab*. 2006;91(3):1093–8.

57. **Frajese G V, Taylor NF, Jenkins PJ, Besser GM, Monson JP.** Modulation of cortisol metabolism during treatment of acromegaly is independent of body composition and insulin sensitivity. *Horm Res*. 2004;61(5):246–51.

58. **Moore JS, Monson JP, Kaltsas G, Putignano P, Wood PJ, Sheppard MC, Besser GM, Taylor NF, Stewart PM.** Modulation of 11beta-hydroxysteroid dehydrogenase isozymes by growth hormone and insulin-like growth factor: in vivo and in vitro studies. *J Clin Endocrinol Metab*. 1999;84(11):4172–7.

59. **Kalinyak JE, Dorin RI, Hoffman AR, Perlman AJ.** Tissue-specific regulation of glucocorticoid receptor mRNA by dexamethasone. *J Biol Chem*. 1987;262(22):10441–4.

**Table Legends:**

**Table 1: Clinical characteristics.** Data represents mean +/- standard error.

**Figure Legends**

**Figure 1: Acromegalic patients have reduced insulin sensitivity and trend for higher lipolytic activity than their controls.** A) Fasting blood glucose levels. B) Fasting insulin levels. C) HOMA-IR score from Control or Acromegaly subjects. D) *ex vivo* lipolysis as measured by glycerol release from excised white adipose tissue from control or acromegaly patients left untreated (Basal) or after stimulation with 30 nM isoproterenol (Iso). Data is presented as mean +/- standard error of the mean. Asterisk indicates q<0.05.

**Figure 2: Differential expression of genes in white adipose tissue from subjects with acromegaly compared to controls.** A) Heatmap of the differentially expressed genes in white adipose tissue. Individual values are colored as the log fold change for a particular gene in a particular subject compared to the average expression of that gene across all cohorts, with brown indicating less expression and green indicating more expression (designated in the key as Row Z-score). The bar across the top indicates the subject’s diagnosis, red for acromegaly and blue for controls.

**Figure 3: GH targets are differentially expressed in acromegaly subjects.** A) mRNA Expression of *IGF1* and *IGFBP3* transcript levels in adipose tissue from control and acromegalic patients (B) Comparason between *IGF1* mRNA and IGF-1 serum levels in patients with acromegaly (C) Expression of mRNA for suppressors of growth hormone signaling (D) and Expression of tyrosine phosphatases associated with growth hormone signaling. Asterisks indicate q<0.05. Barplots are presented as mean +/- standard error of the mean. mRNA Expression is in units of RPKM (reads per kilobase per million reads).

**Figure 4: Expression changes of selected genes, potentially responsible for lipolytic or insulin sensitivity alterations in acromegaly patients.** mRNA Expression profile of genes potentially involved in lipid catabolism (A), regulation of lipolysis (B), fatty acid synthesis (C), fatty acid desaturation (D), *TCF7L2* (E), and glucocorticoid signaling (F). Asterisks indicate q<0.05. Data indicates mean +/- standard error of the mean. mRNA Expression is in units of RPKM (reads per kilobase per million reads).

**Supplementary Data**

**Supplementary Table 1: Expression changes between control and acromegaly subjects.** Calculated expression, and expression changes for each gene are shown along with raw p-value, adjusted p-values and the fold change.

**Supplementary Table 2:** Gene set enrichment analysis of KEGG pathways. Size is the total size of the KEGG category, NES is the normalized enrichment score, NOM p-value is the raw p-value and FDR q-value is corrected for multiple observations. Gene details lists the specific genes which led to the enrichment of this category in our data. A negative enrichment score indicates down-regulation of the category in acromegaly.

**Supplementary Table 3:** Gene set enrichment analysis of gene ontology enrichment categories. Size is the total size of the GO category, NES is the normalized enrichment score, NOM p-value is the raw p-value and FDR q-value is corrected for multiple observations. Gene details lists the specific genes which led to the enrichment of this category in our data. A negative enrichment score indicates down-regulation of the category in acromegaly.

**Supplementary Table 2:** Gene set enrichment analysis of transcription factor and miRNA pathways. These categories indicate that target genes regulated by these factors are altered in acromegalic white adipose tissue. Size is the total size of the category, NES is the normalized enrichment score, NOM p-value is the raw p-value and FDR q-value is corrected for multiple observations. Gene details lists the specific genes which led to the enrichment of this category in our data. A negative enrichment score indicates down-regulation of the category in acromegaly.

**Supplementary Figure 1: Expression changes of selected other transcripts.** mRNA Expression profile of differentially expressed genes involved in A) MAPK Signaling, B) Cell cycle control, C) DNA synthesis and apoptosis D) ASK-1 Signaling and E) Glycogen metabolism. Asterisks indicate q<0.05. Barplots are presented as mean +/- standard error of the mean. mRNA Expression is in units of RPKM (reads per kilobase per million reads).

**Supplementary Figure 2: Expression changes of selected insulin signal transduction genes.** mRNA Expression profile of genes involved in insulin signaling (A) and inflammation (B). Asterisks indicate q<0.05. Barplots are presented as mean +/- standard error of the mean. mRNA Expression is in units of RPKM (reads per kilobase per million reads).

**Supplementary Figure 3: Ceramide levels in adipose tissue from control and acronegalic patients.** Ceramide (Cer) or glucosylceramide levels (GluCer) were determined as described in the methods and materials section. The number indicates the fatty acid species associated with each lipid. All values are normalized such that control values are equal to 1. Data indicates mean +/- standard error of the mean.

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