Growth hormone controls lipolysis by regulation of FSP27 expression

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Abstract

Growth hormone (GH) has long been known to stimulate lipolysis and insulin resistance; however, the molecular mechanisms underlying these effects are unknown. In the present study, we demonstrate that GH acutely induces lipolysis in cultured adipocytes. This effect is secondary to the reduced expression of a negative regulator of lipolysis, fat-specific protein 27 (FSP27; aka Cidec) at both the mRNA and protein levels. These effects are mimicked in vivo as transgenic overexpression of GH leads to a reduction of FSP27 expression. Mechanistically, we show GH modulation of FSP27 expression is mediated through activation of both MEK/ERK- and STAT5-dependent intracellular signaling. These two molecular pathways interact to differentially manipulate peroxisome proliferator-activated receptor gamma activity (PPARγ) on the FSP27 promoter. Furthermore, overexpression of FSP27 is sufficient to fully suppress GH-induced lipolysis and insulin resistance in cultured adipocytes. Taken together, these data decipher a molecular mechanism by which GH acutely regulates lipolysis and insulin resistance in adipocytes.

Introduction

Although growth hormone (GH) has been primarily studied for its effects on linear growth, pronounced stimulation of lipolysis was among the first metabolic effects reported in human subjects following the introduction of pituitary-derived human GH (Raben & Hollenberg 1959). Studies in mice have indicated that ablation of the GH receptor or Jak2 in adipose tissue reduces GH-induced lipolysis (List et al. 2013, Nordstrom et al. 2013, Shi et al. 2014). In addition, pharmacological blockade of the hormone-sensitive lipase (HSL) abrogates the lipolytic effects of GH in human subjects (Nielsen et al. 2001). However, the direct molecular mechanisms by which GH induces lipolysis have not been fully elucidated.
The importance of deciphering this mechanism is clear, as several lines of clinical evidence demonstrate that GH regulates insulin sensitivity in humans as a direct result of its lipolytic action. In both healthy volunteers and patients with GH deficiency, the insulin resistance caused by acute GH treatment is reversed by a pharmacological blockade of lipolysis (Segerlantz et al. 2003, Moller et al. 2009, Salgin et al. 2009, Cornford et al. 2012). Additionally, the ‘dawn phenomenon’, which describes an early morning increase in insulin resistance in diabetic patients, has been directly attributed to the diurnal peak of GH levels (Schmidt et al. 1981, Bolli & Gerich 1984, Monnier et al. 2012, Bouchonville et al. 2014). Strikingly, the dawn phenomenon can be almost entirely corrected by reducing GH levels (Campbell et al. 1985, Davidson et al. 1988) or by blocking the lipolytic action of GH (Salgin et al. 2009). Taken together, these studies demonstrate that GH-mediated lipolysis is a critical regulator of insulin sensitivity in both healthy and diabetic patients.

Lipolysis in adipose tissue requires the sequential activation of several enzymes including the rate-limiting enzyme Adipose triglyceride lipase (ATGL) and hormone-sensitive lipase (HSL) (Zimmermann et al. 2004). The cell death-inducing DNA fragmentation factor alpha-like effector (CIDE) family proteins associate with lipid droplets and regulate fatty acid homeostasis in adipocytes (Puri et al. 2008a,b). CIDEC, also known as FSP27, regulates lipid droplet dynamics and lipolysis in adipocytes through suppression of the catalytic capacity as well as transcription of ATGL (Grahn et al. 2014, Singh et al. 2014). Consistent with these studies, mutation of FSP27 in humans leads to increased lipolysis (Rubio-Cabezas et al. 2009). In addition, adipose-specific disruption of FSP27 causes insulin resistance in high-fat-fed mice (Tanaka et al. 2015).

In the present study, we demonstrate that GH-induced lipolysis is associated with an acute reduction in FSP27 mRNA and protein expression. Mechanistically, we show GH-induced reduction of FSP27 is mediated through GH activation of both MEK/ERK- and STAT5-dependent signaling, which coordinately regulate peroxisome proliferator-activated receptor gamma (PPARγ) transcriptional activity. Finally, we demonstrate that overexpression of FSP27 is alone sufficient to fully repress GH-induced lipolysis and insulin resistance in adipocytes. Taken together, these data clearly demonstrate a transcriptional mechanism by which GH acutely regulates lipolysis and insulin action in adipocytes.

Materials and methods

Mice

bGH and STAT5ΔN/ΔN mice were housed at 22°C under a 14-h light, 10-h darkness cycle, 3–4 mice per cage and ad libitum access to water and standard laboratory chow (ProLab RMH 3000). All experiments were approved by the Ohio University Institutional Animal Care and Use Committee.

Cell culture

3T3-L1 (from ATCC: CL-173; passages 4–12) were grown in DMEM, high glucose (4.5 g/L) supplemented with Glutamax, Pen-Strep and 10% FBS. For differentiation into adipocytes, cells were seeded at 200,000 cells/well in six-well plates. After cells reached confluence, the medium was replaced by differentiation medium (growth medium with 1μM dexamethasone, 0.5μM isobutylmethylxanthine, 100nM insulin and 1μM rosiglitazone. After 2 days, the medium was replaced with growth medium containing 100nM insulin and 1μM rosiglitazone for two more days, then for 2–3 days with growth medium alone.

Lipolysis

Differentiated adipocytes were serum deprived in DMEM, high glucose for 2 hours then treated in KRH buffer supplemented with 2mM sodium pyruvate in the presence or absence of U0126 (1,4-diamo-2,3-dicyano-1,4-bis(2-aminophenylthio)butadiene), rosiglitazone or STAT5 inhibitor and GH for 2 h. The cells were washed carefully and incubated in Krebs Hepes bicarbonate (KRH) buffer supplemented with 2mM sodium pyruvate in the presence or absence of U0126, rosiglitazone or STAT5 inhibitor, and GH for an additional hour. Glycerol release was measured by colorimetric reaction as previously described (Lee et al. 2013).

Real-time RT-PCR

Analysis of gene expression was conducted using real-time reverse transcriptase quantitative PCR (qPCR). TRIzol Reagent (Life Technologies) was used to extract total RNA from adipose tissue samples, and RNA was quantified by measuring absorbance at 260 and 280 nm with a ratio ≥1.8. For a list of real-time primers and sequences see Supplementary Table 1 (see section on supplementary data given at the end of this article).
Western blot analysis and nuclear fractionation

Proteins were extracted from adipose tissue and cells, subjected to SDS-PAGE, transferred to polyvinylidene fluoride membranes and blots were blocked and probed with antibodies as specified in Supplementary Table 2. Protein were quantified as a ratio to the content of β-actin except for Pparγ in the nuclear fractionation studies in which proliferating cell nuclear antigen (PCNA) and glyceraldehyde 3-phosphate dehydrogenase (Gapdh) were utilized as loading controls. Nuclear fractionation was performed utilizing the Rapid, Efficient And Practical (REAP) method as previously described (Suzuki et al. 2010).

Results

GH acutely induces lipolysis and reduces FSP27 expression

In order to determine the effects of GH on lipolysis, we examined the expression of known regulators of lipolysis in the perigonadal adipose tissue of bovine (b) GH mice transgenic mice. bGH mice have serum GH levels of approximately 2µg/mL, leading to a two-fold increase in serum IGF-1 levels (Chen et al. 1990, 1991). In the perigonadal adipose tissue, mRNA levels of ATGL and perilipin were increased 2- and 3-fold, respectively, while levels of FSP27 were reduced by 40% compared to levels in WT controls (Fig. 1A). In order to determine which of these regulators was directly and acutely regulated by GH action, differentiated 3T3-L1 adipocytes were treated with 500ng/µL of recombinant bGH for 2h. qPCR analysis indicates expression of FSP27 was acutely reduced by ~35% by GH treatment, with no changes in mRNA levels of other regulators of lipolysis (Fig. 1B). This GH-mediated decrease in FSP27 mRNA and protein expression was transitory, as qPCR and Western blot analysis indicates that FSP27 mRNA and protein levels were reduced by 35–40% at 2–4h after GH treatment with levels returning to baseline by 12h (Fig. 1C and Supplementary Fig. 1A). On the other hand, the known target gene of GH, insulin-like growth factor I (Igf1) was significantly increased at 4, 12 and 24h after GH treatment (Chia et al. 2010) (Supplementary Fig. 1B). Furthermore, treatment of differentiated 3T3-L1 adipocytes with GH for 2h reveals that lipolysis, as measured by glycerol release, is increased in a dose-dependent manner (Fig. 1D). This increased lipolytic rate is accompanied by a rate dependent decrease in FSP27 mRNA and protein levels at 2h (Fig. 1E and Supplementary Fig. 1C). Thus, in cultured adipocytes, GH treatment directly increases lipolysis that is associated with a rapid and transient decrease in FSP27 expression.

GH regulates lipolysis in a MEK- and PPARγ-dependent manner

Since FSP27 is transcriptionally regulated by PPARγ (Kim et al. 2008, Puri et al. 2008a) and its expression is affected by PPARγ phosphorylation (Choi et al. 2011, Banks et al. 2015, Tan et al. 2016) mediated through MEK/ERK, we investigated if GH modulates PPARγ levels and/or activity through these pathways. Although no changes in total PPARγ protein levels were noted, we did find that the effects on lipolysis are mediated through both MEK/ERK and PPARγ. A 2-h pre-treatment with 10µM U0126,
to block the phosphorylation of MEK, or 1 µM rosiglitazone, to fully activate PPARγ, was sufficient to completely inhibit GH-induced lipolysis (Fig. 2A). Western blot analysis indicates that 20 min of GH treatment induced phosphorylation of ERK on T202/Y204 and STAT5 on Y694 without changes in their total protein levels. Pre-treatment with U0126 abolished ERK phosphorylation without affecting STAT5 phosphorylation, while rosiglitazone pre-treatment had no effect on the phosphorylation of either ERK1 or STAT5. Phosphorylation of HSL at S563 was induced by GH treatment at the 2h time point, and this induction was blunted by U0126, but not significantly altered by rosiglitazone pre-treatment (Fig. 2B and Supplementary Fig. 2A).

Interestingly, both U0126 and rosiglitazone pre-treatment not only prevented GH-induced reduction of
FSP27, but led to a GH-dependent three-fold increase in the level of FSP27 mRNA and protein (Fig. 2C and D). Levels of other regulators of lipolysis including ATGL, HSL, and Cidea were not significantly altered either by U0126 and rosiglitazone pre-treatment or GH treatment. Furthermore, no changes in total PPARγ levels were noted (Fig. 3A and Supplementary Fig. 2B, C, D). Taken together, these data indicate that GH suppresses FSP27 expression through MEK/ERK- and PPARγ-dependent mechanisms.

**GH treatment results in PPARγ translocation to the cytoplasm**

MEK has been shown to directly interact with and phosphorylate PPARγ leading to its nuclear export after stimulation with tetradeoxyacyl phorbol acetate or TNF-α stimulation (Burgermeister et al. 2007, Burgermeister & Seger 2007, Tan et al. 2016). GH also acts through these mechanisms as 3T3-L1 adipocytes treated with 500 ng/mL bGH for 20 min increased phosphorylation of pPPARγ on S112 without affecting total pPPARγ levels. Pre-treatment with 10 µM U0126 abolished this effect, while pre-treatment with rosiglitazone had no effect (Fig. 3A). Nuclear fractionation experiments 1 h after GH treatment, demonstrated that GH leads to a rapid increase in cytoplasmic PPARγ and a reduction in nuclear PPARγ. This translocation was inhibited by both U0126 and rosiglitazone (Fig. 3B). These effects were confirmed by immunofluorescence for PPARγ (green) with nuclei counterstained with DAPI (blue) in 3T3-L1 adipocytes treated with 500 ng/mL bGH for 1 h. GH treatment resulted in a rapid translocation of PPARγ from the nucleus to the cytoplasm.

**Figure 2**

GH regulates lipolysis in a MEK and Pparγ dependent manner. (A) Lipolysis as measured by glycerol release from 3T3-L1 adipocytes treated with 500 ng/mL bGH for 2 h after 2 hours of pre-treatment with 10 µM U0126 or 1 µM Rosiglitazone. Data are shown as mean ± S.E.M. of three independent experiments. Asterisks indicate a significant differences in all panels *P < 0.05; **P < 0.01. (B) Representative Western blot analysis of pERK T202/Y204, total ERK, pSTAT5 Y694, total STAT5, pHSL S563, and total HSL in 3T3-L1 adipocytes treated with 500 ng/mL bGH for either 20 min or 2 h after 2 hours of pre-treatment with 10 µM U0126 or 1 µM Rosiglitazone. Actin is used as a loading control. (C and D) qPCR and Western blot analysis of FSP27 mRNA and protein isolated from cells treated with 500 ng/mL bGH for 2 h after 2 hours of pre-treatment with 10 µM U0126 or 1 µM Rosiglitazone. Actin is used as a loading control. Quantitation of Western blot data are shown as mean ± S.E.M. of four independent experiments.
the cytoplasm in 3T3-L1 adipocytes, and pre-treatment with 10 µM U0126 or 1 µM rosiglitazone blocked this effect (Fig. 3C).

**STAT5 increases PPARγ activity on the FSP27 promoter**

The 3-fold increase of FSP27 mRNA in 3T3-L1 adipocytes that we observed upon U0126 or rosiglitazone pre-treatment and subsequent GH treatment (Fig. 2C) lead us to hypothesize that an additional regulatory mechanism is responsible for FSP27 regulation. Nuclear fractionation indicates that STAT5 translocates to the nucleus in a MEK- and PPARγ-independent manner (Supplementary Fig. 3A). Since STAT5 mediates many GH-dependent effects, we pretreated 3T3-L1 adipocytes with the specific STAT5 inhibitor, CAS 285986-31-4 (Muller et al. 2008). The STAT5 inhibitor reduced GH-induced phosphorylation of STAT5 on Y694 by ~70% without changes in total protein levels (Supplementary Fig. 3B and C). Although pre-treatment with the STAT5 inhibitor alone had limited effect on mRNA levels of FSP27, pre-treatment with STAT5 inhibitor in combination with GH treatment leads to 60% downregulation of FSP27 mRNA. In addition, the STAT5 inhibition completely suppressed the upregulation of FSP27 mRNA that was observed with U0126 and rosiglitazone pre-treatment and subsequent GH treatment and lead to an 80–90% downregulation of FSP27 mRNA (Fig. 4A). Inhibition of STAT5 increased GH-mediated lipolysis by ~15%; however, these results did not quite reach statistical significance (Fig. 4B). Furthermore, qPCR analysis of RNA isolated from subcutaneous and perigonadal fat of mice, which express hypomorphic forms of both Stat5a and Stat5b, STAT5<sup>ΔN/ΔN</sup>-mutant mice

![Figure 3](https://joe.bioscientifica.com)

**Figure 3**

GH treatment results in rapid PPARγ translocation. (A) Representative Western blot analysis of pPPARγ<sup>S112</sup> and total pPPARγ in 3T3-L1 adipocytes treated with 500 ng/mL bGH for 20 min after 2 hours of pre-treatment with 10 µM U0126 or 1 µM Rosiglitazone. (B) Representative Western blot analysis for PPARγ in 3T3-L1 adipocytes treated with 500 ng/mL bGH for 1 h after 2 h of pre-treatment with MEK1 inhibitor, 10 µM U0126, or 1 µM Rosiglitazone following nuclear fractionation. The positive control is whole cell lysate of 3T3-L1 adipocytes. Gapdh and PCNA are loading controls for the cytoplasmic and nuclear fractions, respectively. (C) Immunofluorescence for PPARγ (green) with nuclei counterstained with DAPI (blue) of in 3T3-L1 adipocytes treated with 500 ng/mL bGH for 1 h after 2 h pre-treatment with 10 µM U0126 or 1 µM Rosiglitazone.

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(Teglund et al. 1998, Cui et al. 2004), demonstrates that FSP27 is significantly reduced in the perigonadal fat and tends to be reduced in subcutaneous fat (Fig. 4C).

The dependence of FSP27 expression on both STAT5 and PPARγ prompted us to test whether FSP27 might be directly regulated by the cooperative action of these factors. A reporter construct harboring a 0.9 kb upstream fragment of the human FSP27 gene linked to a luciferase reporter gene (FSP27-luc) was co-transfected with either a vector control or 25 ng of PPARγ expression vector and 25 ng of its obligate heterodimer RXRα. The cells were also co-transfected with either a vector control or 25 ng of a STAT5 expression vector. Luciferase assays demonstrated that basal FSP27 promoter activity in 293T cells was very low, and no change in activity was seen following STAT5 expression. The FSP27-luc activity was potently activated by co-transfection of PPARγ and its obligate heterodimer partner RXRα. Although we could not detect direct interaction between PPARγ and STAT5 (Supplementary Fig. 3D), co-transfection of STAT5 with PPARγ resulted in a synergistic 50% increase in FSP27-luc activation compared to PPARγ alone (Fig. 4D). Both STAT5A and STAT5B were equally able to transactivate the FSP27 promoter construct when co-transfected with PPARγ, while a constitutively active form of STAT5B (Kim et al. 2010) lead to further transactivation of the promoter construct (Supplementary Fig. 3E).

Examination of the FSP27 promoter sequence revealed the presence of half of a consensus STAT-binding site (StatRE) adjacent to the known PPARγ response element (PPRE) (Kim et al. 2008). Site-directed mutagenesis of the PPRE (APPRE) in the FSP27 promoter abolishes its response to both PPARγ and STAT5 (Fig. 4E). On the other hand, mutation of the StatRE (ΔStatRE) does not significantly affect activation either by PPARγ or co-transfection of PPARγ and STAT5 (Fig. 4F).

**FSP27 over-expression prevents GH-induced lipolysis and insulin resistance**

Our data indicate that GH-induced lipolysis is associated with a reduction of FSP27 expression. Thus, we hypothesized that FSP27 over-expression might protect adipocytes from GH-induced lipolysis and insulin resistance. To test our hypothesis, we utilized adenovirus to stably over-express human FSP27 in 3T3-L1 adipocytes. Interestingly, FSP27 over-expression in adipocytes almost completely suppressed GH-induced lipolysis (Fig. 5A and B). Furthermore, since lipolysis is associated with lipid droplet fragmentation (Walther et al. 2012), we assessed lipid droplet number in control and FSP27 over-expressing cells. Control 3T3-L1 adipocytes each contained ~20 lipid droplets/cell, and 24 h of GH treatment leads to over a five-fold increase in the number of lipid droplets. FSP27 over-expression was sufficient to completely abolish the effect GH on lipid fragmentation (Fig. 5C and Supplementary Fig. 4A). Since the FFAs liberated by lipolysis have long been known to cause insulin resistance (Boden 1997), we assessed the insulin-stimulated phosphorylation of AKT S473 in these adipocytes. Treatment of control adipocytes with 10nM insulin for 15 min strongly induces phosphorylation of AKT on S473, while pre-treatment with 250ng/mL GH for 2h reduced this phosphorylation by ~60%. However, the inhibitory effect of GH on AKT on S473 phosphorylation was abolished in adipocytes over-expressing FSP27 (Fig. 5D and Supplementary Fig. 4B). Thus, over-expression of FSP27 is sufficient to prevent GH-induced lipolysis, lipid fragmentation, and insulin resistance.

**Discussion**

In the present study, we present a molecular mechanism by which GH regulates lipolysis in adipose tissue. These studies are consistent with human studies in adipose tissue, as GH receptor levels have been shown to be directly correlated with FSP27 levels in human subcutaneous adipose tissue (Karastergiou et al. 2016) and acute infusion of 30 ng/min of GH in human subjects is sufficient to induce lipolysis and leads to reduction in FSP27 expression at the mRNA and protein levels (Sharma V, et al. submitted manuscript). Our data demonstrate that GH-induced MEK/ERK activation promotes PPARγ phosphorylation and translocation from the nucleus. This serves as the dominant pathway controlled by GH and led to reduced trancription of FSP27. As a counter-regulatory mechanism, GH-induced phosphorylation of STAT5, which enhances PPARγ activity on the FSP27 promoter. Together, these intersecting pathways act together to tightly regulate the lipolytic effects GH (Fig. 5E).

The molecular mechanisms described in this study indicate that GH-induced lipolysis is secondary to its reduction in the expression of FSP27. This mechanism is distinct from previous studies describing pathways by which GH chronically induces lipolysis through HSL activation (Dietz & Schwartz 1991, Bergan et al. 2013). In agreement with these previous findings, we also observed an increase in the MEK/ERK-mediated phosphorylation of HSL (Fig. 2B). However, since ATGL...
hydrolysis of triglycerides is the first and rate-limiting step in lipolysis, it suggests that the changes in the ATGL activity by modulation of FSP27 may be the key regulatory step in control of GH-induced lipolytic rate. Furthermore, except in cases of acromegaly, GH secretion is pulsatile and regulated in diurnal rhythms (Ho et al. 1987). This pulsatile secretion leads us to espouse a biological model by which GH acutely and transiently regulates lipolysis over the effects observed in cellular models of chronic GH treatment. Interestingly, FSP27 levels are chronically, rather than transiently, reduced in bGH animals with consistently high GH levels. bGH has similar somatotropic effects as hGH, but does not bind the prolactin receptor, and thus, does not have the severe lactogenic and reproductive effects observed upon over-expression of hGH effects (Posner 1976, Bartke et al. 1992, 1994). In addition to reduced fat mass, bGH mice also have numerous changes within their adipose tissue, including increased immune cell infiltration within adipose tissue, increased circulating levels of inflammatory cytokines and dramatically altered adipokine expression (Wang et al. 2007, Benencia et al. 2015, Berryman & List 2017). All these factors have been shown to affect FSP27 expression (Tan et al. 2016, Berryman & List 2017) and may contribute to its chronically reduced expression in bGH adipose tissue.

In contrast to the extremely rapid kinetics of catecholamine-induced lipolysis, in which measurable FFA release occurs within minutes, administration of a physiological GH bolus has been shown to stimulate lipolysis after a time lag of 2–3 h (Moller et al. 1990, Morimoto et al. 2001). Consistent with this, the expression of FSP27 is reduced 2 h after GH treatment (Fig. 1B and C). Since FSP27 protein is very unstable and has a short half-life of ~15 min (Nian et al. 2010, Yang et al. 2011), our data indicate that the reduced PPARγ-dependent transcription caused by GH leads to a rapid reduction in its mRNA and protein expression. Importantly, levels of other regulators of lipolysis including Atgl, Hsl, Cidea and CGI-58 are not

Figure 4
STAT5 and PPARγ regulate FSP27 expression. (A) qPCR analysis of FSP27 in RNA isolated from 3T3-L1 adipocytes treated with vehicle or 500 ng/mL bGH for 2 h after 2 hours of pre-treatment with 10 µM U0126, 1 µM Rosiglitazone, or 200 µM STAT5 inhibitor. Data are shown as mean ± s.e.m. of three independent experiments. Asterisks indicate a significant difference in all panels *P<0.05; **P<0.01; ***P<0.001. (B) Lipolysis as measured by glycerol release from 3T3-L1 adipocytes treated with vehicle or 500 ng/mL bGH for 2 h after 2 hours of pre-treatment with 200 µM STAT5 inhibitor. Data are shown as mean ± s.e.m. of two independent experiments, each with three replicates/group. (C) Expression level of FSP27 mRNA was compared using quantitative real-time PCR (qPCR) of RNA isolated from subcutaneous (SC) and perigonadal (PG) fat of 4 month old male Stat5ΔN/ΔN mice. Data are shown as mean ± s.e.m. of six samples. (D, E and F) Luciferase activity of 293T cells transfected with a 0.9-kb WT FSP27 luciferase reporter, with the PPARγ response element mutated, or with a presumptive STAT5 response element mutated. The reporter vector was co-transfected either a vector control or 25 ng of PPARγ expression vector and 25 ng of its obligate heterodimer RXRα. The cells were also co-transfected with either a vector control or 25 ng of a STAT5 expression vector. Data are shown as mean ± s.e.m. of three independent experiments, each with three replicates.
Acutely changed by GH treatment. Furthermore, although chronic GH treatment upregulates transcription of PPARγ mRNA in a STAT5-dependent manner (Kawai et al. 2007), the acute lipolytic effects of GH occur in the absence of increased PPARγ expression (Fig. 4A). In addition, these effects are also independent of IGF1, as levels of IGF-1 remain unchanged after 2 h of GH treatment in cultured adipocytes (Supplementary Fig. 2A). Although we could not detect direct protein-protein interaction of STAT5 and PPARγ (Supplementary Fig. 3D), our data clearly indicate that STAT5, in a GH-dependent manner, is critical for maintaining FSP27 expression and may play a role in moderating the magnitude of GH-induced lipolysis (Fig. 4A and B). Treatment with the STAT5 inhibitor tended to increase lipolysis; this difference did not quite reach statistical significance. This may be due to the secondary role of STAT5 pathway in this process, as the MEK/ERK is the predominant pathway. In addition, the STAT5 inhibitor did not fully suppress STAT5 phosphorylation, thus limiting its effect on lipolysis. Elucidating the exact molecular mechanism by which STAT5 controls PPARγ activity will be of importance in future studies.

Our data demonstrate that reduction of lipolysis by over-expression of FSP27 blocks the GH-mediated suppression of insulin signaling in adipocytes. These results are in agreement with previous reports that
indicate circulating FFAs are the dominant inducer of insulin resistance and non-suppressible hepatic glucose production in patients with T2DM (Titchenell et al. 2016). Furthermore, both current and early studies have consistently demonstrated that acute administration of GH has a strong diabetogenic effect that is primarily due to its lipolytic action (Houssay 1936, Segerlantz et al. 2003, Møller et al. 2009, Salgin et al. 2009, Cornford et al. 2012). These diabetogenic effects of GH are also manifested in acromegalic patients with high levels of GH that display increased rates of insulin resistance, hyperinsulinemia and type 2 diabetes (Rizza et al. 1982, Hansen et al. 1986, Melmed et al. 2009). This induction of insulin resistance is, in all likelihood, a critical part of the response of adipocytes to GH, as it serves to inhibit the anti-lipolytic action of insulin (Okada et al. 1994) and allows lipolysis to proceed. Although previous experiments in mice have shown that the diabetogenic effect of GH can, at least in part, be explained by alterations in the ability of insulin to activate PI-3 kinase in insulin target cells (Dominici et al. 2005, del Rincon et al. 2007), studies in humans have questioned the role of PI-3 kinase in GH-induced insulin resistance (Jessen et al. 2005, Nielsen et al. 2008, Krusenstjerna-Hafstrom et al. 2011a,b). Importantly, the ‘dawn phenomenon’, which describes an early morning increase in insulin resistance in patients with diabetes, can be almost entirely corrected by reducing GH levels or GH-induced lipolysis (Campbell et al. 1985, Davidson et al. 1988, Salgin et al. 2009). Although the dawn phenomenon was first described in type 1 diabetes mellitus (T1DM), recent studies utilizing the advent of continuous glucose monitoring systems has demonstrated the dawn phenomenon occurs in ~50% of patients with both T1DM and T2DM, significantly increases HbA1c levels (~0.4% in T2DM) and leads to frequent hyperglycemic episodes (Monnier et al. 2012, 2013, Bouchonville et al. 2014). Taken together, these studies demonstrate that GH-mediated lipolysis is a critical regulator of insulin resistance in both healthy subjects and patients with diabetes.

Clinical studies have consistently demonstrated that GH treatment reduces visceral fat mass and improves metabolic parameters in GH-deficient patients, as well as those with visceral obesity (Beauregard et al. 2008, Bredella et al. 2013). This reduction in visceral fat mass is presumably, at least in part, due to lipolytic action of GH. On the other hand, in diabetic patients, GH-induced lipolysis leads to frequent hyperglycemic episodes in the dawn phenomenon (Monnier et al. 2012, 2013, Bouchonville et al. 2014). Thus, understanding the molecular mechanisms which underlie GH-induced lipolysis is crucial for the treatment of a wide variety of patients. Our studies identify several molecular targets of intervention to manipulate GH-induced lipolysis. Many of these targets already have pharmacological agents in clinical use, including MEK inhibitors (Trametinib), PPARγ agonists (Thiazolidinediones) and anti-lipolytic agents (Acipimox). Therefore, we strongly believe that these data have clear bench to bedside ramifications and can have significant and immediate clinical impact.

Supplementary data
This is linked to the online version of the paper at https://doi.org/10.1530/JOE-18-0282.

Declaration of interest
The authors declare that there is no conflict of interest that could be perceived as prejudicing the impartiality of the research reported.

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Author contribution statement
R S, Q L, V M S, M H, B H, A C, and D E B designed and performed experiments; J J K, J O L J, N J and V P designed experiments and analyzed data; K Y L designed and performed experiments, analyzed data and wrote the paper.

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