Palmitate acutely induces insulin resistance in isolated muscle from obese but not lean humans

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The objectives of the present study were to determine whether 1) 4 h of exposure to high concentrations of palmitate would impair insulin signaling, glucose transport, and FA oxidation in isolated human rectus abdominus muscle; 2) whether muscle derived from obese subjects was more susceptible to FA-induced insulin resistance than from lean subjects; 3) whether the presence of gAd in the incubation medium could prevent/blunt the insulin desensitizing effects of palmitate; and 4) finally, AdipoR1 protein content was measured in muscles from lean and obese subjects, as this had not previously been reported and could potentially explain differences in gAd action in skeletal muscle from lean and obese humans.
We hypothesized that palmitate would induce insulin resistance to a greater degree in muscle from obese individuals and that this would be at least partially corrected by gAd. We also hypothesized that AdipoR1 protein content would be reduced in skeletal muscle from obese individuals and that this may, in part, explain the reduced responsiveness to gAd in obese muscle.

METHODS

Subjects. Nineteen lean (body mass index <26 kg/m², mean 24.0 ± 0.6 kg/m²) and 16 obese (body mass index >29 kg/m², mean 35.4 ± 2.1 kg/m²) women participated in this study. Subjects were admitted to McMaster Medical Centre in Hamilton, ON, for abdominal hysterectomies or other abdominal surgeries. Subjects gave informed written consent prior to participating in this study. This study adhered to the principles of the declaration of Helsinki Code and was approved by McMaster University and University of Guelph ethics committees. All subjects had maintained the same body mass for the past year, were nondiabetic, nonsmokers, and sedentary. Subjects were screened for any medications (e.g., to control blood pressure or lipids, glucose tolerance, etc.) or diseases that might interfere with the results of the study.

Sample preparation. Following an overnight fast (12–18 h) general anesthesia was induced with a short-acting barbiturate and maintained by a fentanyl and rocuronium volatile anesthetic mixture. Venous blood samples were collected in a 5-ml sodium-heparinized tube during anesthesia. A skeletal muscle biopsy (3 × 2 × 1 cm) from the rectus abdominis was excised at resting length perpendicular to the direction of the muscle fibers and placed immediately into gassed, modified, ice-cold Krebs-Henseleit buffer (KHB) containing 8 mmol/l glucose for transport to the laboratory (~5 min). In the same ice-cold buffer solution, 6–11 muscle strips weighing ~25 mg were separated from the muscle sample and clamped at resting length. Any additional tissue not used for incubations was immediately frozen in liquid nitrogen and stored for the analysis of AdipoR1.

The experimental protocol is shown in Fig. 1. Muscle samples were placed immediately in gassed (95%O₂-5% CO₂) preincubation KHB containing 8 mmol/l glucose and 4% BSA (FA free), for 20 min in a shaking water bath at 30°C. Muscle samples were then transferred into incubation buffers of control (same as preincubation buffer control); 2 mM palmitate or 2 mM palmitate + 2.5 μg/ml gAd (P+gAd; recombinant human gAd; cat. no. 450-21; Peprotech, Ottawa, ON, Canada) and incubated for 4 h. Muscle strips were washed (2 × 10 min) with glucose-free KHB containing 4 mM pyruvate and 36 mM mannitol. Muscle strips were then incubated for 20 min (insulin) or 40 min (basal) in KHB containing 4 mM pyruvate, 8 mM 3-O-[1⁴C]methyl-d-glucose (0.8 μCi/ml) and 32 mM [¹⁴C]mannitol (0.3 μCi/ml). Glucose transport was determined as the accumulation of intracellular 3-O-[¹⁴C]methyl-d-glucose.

FA metabolism. FA metabolism was assessed during the final hour of the 4 h incubation period. Briefly, muscles incubated in either palmitate or P+gAd were transferred to a 20-ml glass scintillation vial containing 2 ml of the same incubation buffer, but with the addition of 0.5 μCi/ml of [1-¹⁴C]palmitate (Amersham, Oakville, ON, Canada) to measure exogenous palmitate oxidation and the incorporation of palmitate into endogenous lipid pools as previously described (25).

Western blot analysis. Following 4 h of incubation in either control, palmitate, or P+gAd, muscle samples were transferred to a vial containing the same incubation buffer with the addition of 0.5 μCi/ml of [¹³C]palmitate (Amersham, Oakville, ON, Canada) to measure exogenous palmitate oxidation and the incorporation of palmitate into endogenous lipid pools as previously described (25).

Fig. 1. Experimental protocol. C, control; P, palmitate; gAd, globular adiponectin; pre-inc, preincubation.
Plasma adiponectin was significantly lower (significantly higher in obese individuals) compared with lean individuals. Blood glucose and body mass index were not different following exposure to palmitate or P+gAd in lean or obese individuals (Fig. 2, A and B). Insulin-stimulated glucose transport was significantly increased compared with basal glucose transport under all conditions in both lean and obese individuals (P < 0.001; Figs. 2, A and B).

In lean individuals, there was no significant difference in insulin-stimulated glucose transport with exposure to palmitate (−10%) or P+gAd (+3%) compared with control (Fig. 3A). The absolute increase in glucose transport from basal to insulin-stimulated conditions (Fig. 2C) was not significantly different among the three incubation conditions in this population (P = 0.66).

In contrast, insulin-stimulated glucose transport was reduced by 20% in isolated muscle from obese individuals when exposed to palmitate (P+gAd vs. control, P = 0.003). When gAd was also included (Fig. 2B), there was a trend toward a reduction in insulin-stimulated glucose transport compared with control (control vs. P+gAd, −12%, P = 0.09). The inclusion of gAd tended to increase insulin-stimulated glucose transport compared with palmitate (+15%), but this also did not reach significance (P+gAd vs. palmitate, P = 0.07). When glucose transport was expressed as an absolute increase in response to insulin, both palmitate and P+gAd conditions were significantly lower than control, (palmitate vs. control, −55%; P+gAd vs. control, −36%, P = 0.05). There was no significant difference in the absolute increase in glucose transport between palmitate and P+gAd in skeletal muscle from obese individuals (P+gAd vs. palmitate, P = 0.3). This indicates that palmitate induced insulin resistance in skeletal muscle from obese individuals, but the inclusion of gAd was unable to completely prevent this.

Insulin-signaling proteins. The effects of palmitate and P+gAd conditions relative to control on Ser- and Thr-phosphorylated Akt, unphosphorylated Akt, and P-AS160 following acute insulin stimulation in lean and obese individuals are shown in Fig. 3. Palmitate or P+gAd did not significantly affect insulin-signaling protein content or phosphorylation in muscle from lean individuals (total Akt, Thr Akt, Ser Akt, P-AS160; Fig. 3, A, C, E, and G, respectively). In skeletal muscle samples, phospho-Akt content, but not total Akt, was decreased by 10.2 ± 0.33 compared to control (control vs. palmitate, P = 0.003). When gAd was also included (Fig. 2B), there was a trend toward a decrease in phospho-Akt content compared with control (control vs. P+gAd, −12%, P = 0.09). The inclusion of gAd tended to increase phospho-Akt content compared with palmitate (+15%), but this also did not reach significance (P+gAd vs. palmitate, P = 0.07). When phospho-Akt was expressed as an absolute increase in response to insulin, both palmitate and P+gAd conditions were significantly lower than control, (palmitate vs. control, −55%; P+gAd vs. control, −36%, P = 0.05). There was no significant difference in the absolute increase in phospho-Akt content between palmitate and P+gAd in skeletal muscle from obese individuals (P+gAd vs. palmitate, P = 0.3). This indicates that palmitate induced insulin resistance in skeletal muscle from obese individuals, but the inclusion of gAd was unable to completely prevent this.

**Table 1. Subject characteristics**

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Lean</th>
<th>Obese</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age, yr</td>
<td>47±2</td>
<td>47±2</td>
</tr>
<tr>
<td>Body mass, kg</td>
<td>61.0±2.5</td>
<td>94.8±6.3†</td>
</tr>
<tr>
<td>BMI, kg/m²</td>
<td>24.0±2.0</td>
<td>35.4±2.1‡</td>
</tr>
<tr>
<td>Fasting blood glucose, mmol/l</td>
<td>5.0±0.1</td>
<td>5.5±0.4</td>
</tr>
<tr>
<td>Fasting plasma insulin, pmol/l†</td>
<td>22.2±1.0</td>
<td>33.2±4.8†</td>
</tr>
<tr>
<td>HOMA-IR</td>
<td>5.0±0.3</td>
<td>8.0±1.2‡</td>
</tr>
<tr>
<td>Fasting free fatty acid, mmol/l</td>
<td>0.89±0.06</td>
<td>0.92±0.03</td>
</tr>
<tr>
<td>Fasting plasma adiponectin, µg/ml</td>
<td>13.0±0.5</td>
<td>7.5±1.5*</td>
</tr>
<tr>
<td>Fasting plasma leptin, ng/ml</td>
<td>12.2±2.6</td>
<td>36.6±5.4*</td>
</tr>
</tbody>
</table>

Data are means ± SE. BMI, body mass index; HOMA-IR, homeostasis model of assessment comparing insulin resistance. *Significantly different from lean, 1-tailed unpaired t-test (P < 0.01); †significantly different from lean, 1-tailed unpaired t-test (P < 0.05), ‡significantly different from lean, 1-tailed unpaired t-test (P < 0.0001).

The homeostasis model of assessment used to compare insulin resistance was significantly greater in obese individuals (P < 0.05), indicative of whole body insulin resistance in this population.

Skeletal muscle glucose transport. Basal glucose transport was not different following exposure to palmitate or P+gAd in lean or obese individuals (Fig. 2, A and B). Insulin-stimulated glucose transport was significantly increased compared with basal glucose transport under all conditions in both lean and obese individuals (P < 0.001; Figs. 2, A and B).

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muscle from obese individuals, total Akt was not different following palmitate or P+gAd exposure relative to control (Fig. 3B). There was a nonsignificant reduction in Thr Akt phosphorylation following treatment with palmitate (−35%) and P+gAd (−37%) compared with control (Fig. 3D, \( P = 0.13 \)). Ser Akt phosphorylation was significantly reduced (−58%) when exposed to palmitate in skeletal muscle of obese individuals (Fig. 3F, control vs. palmitate, \( P < 0.001 \)). When gAd was included with palmitate, Ser Akt phosphorylation remained significantly reduced (−39%) compared with control (control vs. P+gAd, \( P < 0.001 \)). In the presence of gAd, Ser Akt phosphorylation tended to be increased compared with palmitate (palmitate vs. P+gAd, \( P = 0.07 \)). Phosphorylated AS160 (Fig. 3H) was also significantly reduced following exposure to palmitate (−32%) and P+gAd (−38%) in muscle from obese individuals (control vs. palmitate, control vs. P+gAd, \( P < 0.05 \)).

**Skeletal muscle FA metabolism.** The effects of palmitate and P+gAd on FA metabolism are shown in Table 2 and Fig. 4. The inclusion of gAd resulted in increased palmitate oxidation (Fig. 4) and total palmitate uptake (Table 2) in muscle from both lean and obese individuals (Fig. 4, \( P < 0.05 \)). There was no significant difference in FA incorporation into lipid pools in the presence of gAd in skeletal muscle of lean or obese individuals compared with palmitate (Table 2).

**AdipoR1.** AdipoR1 protein content was 20% lower in skeletal muscle of obese individuals; however, this was not significant (Fig. 5).

**DISCUSSION**

This study demonstrated that 4 h of 2 mM palmitate exposure can induce insulin resistance in isolated rectus abdominus muscle from obese but not lean individuals; this coincided with impaired Ser Akt and AS160 phosphorylation, which were also only apparent in the obese muscle. The inclusion of gAd did not restore insulin-stimulated glucose transport to control values or prevent the reduced phosphorylation of Ser Akt and AS160. In the presence of high palmitate, gAd was still able to stimulate FA oxidation in both lean and obese muscle, suggesting that the inability to restore insulin sensitivity was not fully a function of gAd resistance. It may be possible that under acute (4 h) conditions, either stimulating FA oxidation was insufficient, or the magnitude of the stimulation was not large enough to prevent palmitate-induced insulin resistance in obese individuals. There was a small, nonsignificant reduction (−20%) in AdipoR1 protein content in obese muscle compared with lean. It is uncertain whether this was a physiologically relevant reduction. Perhaps indicative of the change in AdipoR1 being nonrelevant was our observation that gAd was still able to stimulate FA oxidation, although this was slightly lower in obese than in muscle from lean individuals.

Isolated rectus abdominus muscle strips, as used in the present study, are a unique model that allows for the in vitro assessment of human muscle metabolism in isolation of systemic influences (15). Rectus abdominus muscle has a relatively even distribution of Type I and IIa fibers, with a small portion of Type IIb fibers, making it slightly less glycolytic but comparable to the more commonly used vastus lateralis muscle (26). Furthermore, citrate synthase activity is similar between rectus abdominus and vastus lateralis, which indicates a comparable oxidative capacity (7). It should be recognized that, as with any in vitro model, extrapolation to the in vivo condition must be cautious. Furthermore, other skeletal muscles/fiber types may not necessarily respond similarly.
Effect of palmitate and gAd on skeletal muscle glucose transport. The exposure of skeletal muscle to 2 mM palmitate for 4 h induced insulin resistance in skeletal muscle of obese, but not lean, individuals. Skeletal muscle of obese individuals is often characterized by impaired glucose transport (7, 19) and abnormal FA metabolism (20), including increased sarcolemmal FAT/CD36 content (6, 21) and increased lipid content (6, 18). Due to an increased tendency to take up and store FA, it is reasonable to hypothesize that this population is more susceptible to palmitate-induced insulin resistance, which is demonstrated by the findings of this study. It is perhaps surprising that we did not demonstrate a palmitate-induced decrease in insulin-stimulated glucose transport in muscle from lean individuals. However, it is possible that a longer exposure to palmitate, i.e., 6 h, would indeed have induced insulin resistance, which has previously been shown in isolated soleus muscle.

Fig. 3. Insulin signaling in skeletal muscle of lean and obese humans. The effect of 4 h of incubation in control, 2 mM palmitate, or (P+gAd) on insulin-signaling protein content and phosphorylation in skeletal muscle from lean (n = 7) and obese (n = 8) humans. Each muscle sample underwent insulin stimulation during the last 10 min of the incubation. Unphosphorylated Akt (A and B), Thr phosphorylated Akt (C and D), Ser phosphorylated Akt (E and F), and phosphorylated AS160 (P-AS160; G and H) are shown here. Data are means ± SE, expressed as % control within each group (lean, obese). Bars that have different letters are significantly different from each other, P ≤ 0.05, one-way ANOVA; bars that share the same letter are not significantly different.
Table 2. Fatty acid incorporation into DAG and TAG pools

<table>
<thead>
<tr>
<th>Fatty Acid Metabolism</th>
<th>Lean Palmitate</th>
<th>Palmitate + gAd</th>
<th>Obese Palmitate</th>
<th>Palmitate + gAd</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Lipid Incorporation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DAG</td>
<td>29.0 ± 4.2</td>
<td>27.5 ± 4.9</td>
<td>25.9 ± 4.4</td>
<td>22.7 ± 3.8</td>
</tr>
<tr>
<td>TAG</td>
<td>50.2 ± 8.3</td>
<td>61.4 ± 8.7</td>
<td>48.2 ± 9.1</td>
<td>45.1 ± 10.2</td>
</tr>
<tr>
<td>Total</td>
<td>81.1 ± 12.3</td>
<td>81.7 ± 13.2</td>
<td>75.4 ± 12.1</td>
<td>67.5 ± 14.2</td>
</tr>
<tr>
<td>Total palmitate uptake</td>
<td>108.9 ± 10.4</td>
<td>162.8 ± 21.3*</td>
<td>125.4 ± 15.7</td>
<td>156.5 ± 21.8*</td>
</tr>
<tr>
<td><strong>Oxidation-to-Esterification Ratio</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>OX/DAG</td>
<td>1.8 ± 0.3</td>
<td>2.8 ± 0.8</td>
<td>2.4 ± 0.4</td>
<td>3.7 ± 1.0</td>
</tr>
<tr>
<td>OX/TAG</td>
<td>1.0 ± 0.1</td>
<td>0.9 ± 0.1</td>
<td>1.4 ± 0.2</td>
<td>2.4 ± 0.4</td>
</tr>
</tbody>
</table>

Data are means ± SE in nmol/g; lean individuals, n = 5; obese individuals, n = 8. DAG, diacylglycerol; TAG, triacylglycerol; P + gAd, palmitate + globular adiponectin; OX, oxidation. Oxidation-to-esterification ratio: palmitate oxidation, nmol/g (shown in Figure 5). *P vs. P + gAd, P < 0.05, 1-tailed paired t-test.

In the present study, the stimulatory effects of gAd in the absence of palmitate were not measured due to the limited number of viable strips that could be procured for incubation from a given rectus abdominus sample. As a result, we cannot conclude whether gAd was able to independently stimulate glucose transport. However, it has previously been shown in rectus abdominus muscle strips that gAd increases basal and insulin-stimulated glucose transport (7). It is quite possible that the presence of a high palmitate concentration (P + gAd condition) may have prevented this additive effect, i.e., induced gAd resistance.

Effects of palmitate and gAd on insulin-signaling proteins. The present study demonstrated that exposure to palmitate significantly reduced Ser Akt phosphorylation (−58%) and tended to reduce Thr Akt phosphorylation (−35%) under insulin-stimulated conditions. This is in agreement with previous studies in rat soleus muscle (27) and C2C12 muscle cells (9). In accordance with the reduction in Akt phosphorylation, AS160 phosphorylation was also reduced by 35%, which has also been shown in rodent soleus muscle (1). In C2C12 myocytes exposed to palmitate, ceramide content increased and inhibited insulin signaling by stimulating the dephosphorylation of Akt (9), therefore preventing the phosphorylation of AS160. In the present study, the impaired insulin-stimulated glucose transport in muscle from obese individuals may also have been the result of palmitate-induced ceramide production, which prevented the phosphorylation of Akt and AS160. In skeletal muscle from lean individuals, palmitate exposure had...
no significant effect on any of the insulin-signaling proteins that were measured, consistent with the lack of impairment in insulin-stimulated glucose transport. Due to tissue constraints, ceramide content and other lipids were not measured in this study, and so a definitive role of reactive lipid species cannot be determined.

**Effects of palmitate and gAd on FA metabolism.** gAd stimulates FA oxidation in human (7, 11) and rodent (24, 32) muscle. However, obesity may reduce the sensitivity of muscle to the acute stimulatory effects of gAd on AMPK activation and FA oxidation. For example, a greater concentration of gAd is required to stimulate FA oxidation in myotubes cultured from obese human muscle (11). Also, gAd-stimulated FA oxidation is blunted in isolated muscle from obese, compared with lean, humans (7). In addition to this, gAd fails to stimulate FA oxidation in isolated rat soleus muscle following 4 wk of high-fat feeding (24).

In the present study, gAd stimulated FA oxidation in the presence of high palmitate in muscle from both lean and obese individuals. This finding differs from our previous report (7) in which gAd-induced FA oxidation was significantly impaired in obese muscle. However, in our previous study, which used a 0.5 mM palmitate incubation medium, and a shorter period of exposure, gAd stimulated FA oxidation in skeletal muscle of lean and obese humans by 69% and 30%, respectively (7). In the present study, the relative increase in FA oxidation was much less: ~30% in lean, and ~20% in skeletal muscle from obese individuals. Indirectly, this suggests that the longer exposure to a high palmitate concentration may have reduced the stimulatory effects of gAd on FA oxidation.

The fact that palmitate-induced insulin resistance was not alleviated in obese muscle by gAd strongly suggests that the stimulatory effects of gAd on FA oxidation were insufficient to prevent insulin resistance. Whether a greater increase in palmitate oxidation would have proved beneficial is unknown. However, it should be noted that the stimulatory effect of gAd on palmitate oxidation was slightly reduced in obese (+20%) compared with lean (+30%) individuals; Accordingly, we did not observe any impairment in insulin-signaling proteins in the presence of palmitate, with or without gAd in muscle from lean individuals. Overall, the data indicates that obese muscle is more susceptible to the detrimental effect of palmitate, and this could not be rescued with gAd. Furthermore, our data suggests that high palmitate impairs the ability of gAd to independently stimulate glucose transport prior to any loss of stimulation of FA oxidation, i.e., acute development of gAd resistance.

**AdipoR1.** The regulation of AdipoR1 expression in human skeletal muscle is controversial. Findings of decreased, unchanged, and increased mRNA content in muscle from obese and type 2 diabetic individuals have been reported (3, 11). To the best of our knowledge, ours is the first study to examine AdipoR1 protein content in lean and obese human skeletal muscle. Here, we demonstrate a nonsignificant 20% reduction in AdipoR1 content in skeletal muscle from obese individuals. It is uncertain whether this modest reduction in AdipoR1 protein content in obese individuals translates into a physiological reduction in the stimulatory effects of gAd; however, it has previously been shown that the stimulatory effects of gAd are reduced in obesity (7). The fact that we were able to demonstrate gAd-induced stimulation of palmitate oxidation in obese muscle, albeit to a somewhat lesser extent than was observed in lean muscle, suggests that there may not have been a physiologically important reduction in this receptor. Unfortunately, this finding does not clarify the current controversy regarding the regulation of AdipoR1 in lean and obese muscle.

**Perspectives and Significance**

There are several important and novel findings of this study. First and most importantly, we demonstrated that in a 4-h period, 2 mM palmitate directly induces insulin resistance in isolated skeletal muscle from obese, but not lean, individuals. This is consistent with our observed palmitate-induced inhibition of AS160 and Akt phosphorylation in the obese group. Also of significance was the inability of gAd to restore skeletal muscle insulin-stimulated glucose transport in the presence of high palmitate in this group, despite a small, albeit significant, stimulation of palmitate oxidation. The accumulation of lipid species (ceramide and diacylglycerol) have not yet been measured in intact human muscle exposed to palmitate, and should be assessed as a potential mediator of lipid-induced insulin resistance in this model.

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We acknowledge the invaluable contribution of the surgeons Drs. Sibley and Lightheart and particularly the contribution of Dr. Loopstra who recently passed away. We also acknowledge the contribution of the individuals who participated in this study. Finally, the authors acknowledge Ian Ritchie for his technical assistance in this study.

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Effects of palmitate and \( g\)Ad in human muscle


