Skeletal muscle lipid metabolism with obesity

Matthew W. Hulver, Jason R. Berggren, Ronald N. Cortright, Ronald W. Dudek, R. Peter Thompson, Walter J. Pories, Kenneth G. MacDonald, Gary W. Cline, Gerald I. Shulman, G. Lynis Dohm, and Joseph A. Houmard. Skeletal muscle lipid metabolism with obesity. Am J Physiol Endocrinol Metab 284: E741–E747, 2003. First published December 27, 2002; 10.1152/ajpendo.00514.2002.—The objectives of this study were to 1) examine skeletal muscle fatty acid oxidation in individuals with varying degrees of adiposity and 2) determine the relationship between skeletal muscle fatty acid oxidation and the accumulation of long-chain fatty acyl-CoAs. Muscle was obtained from normal-weight (n = 8; body mass index (BMI) 23.8 ± 0.58 kg/m²), overweight/obese (n = 8; BMI 30.2 ± 0.81 kg/m²), and extremely obese (n = 8; BMI 53.8 ± 3.5 kg/m²) females undergoing abdominal surgery. Skeletal muscle fatty acid oxidation was assessed in intact muscle strips. Long-chain fatty acyl-CoA concentrations were measured in a separate portion of the same muscle tissue in which fatty acid oxidation was determined. Palmitate oxidation was 58 and 83% lower in skeletal muscle from extremely obese (44.9 ± 5.2 nmol·g⁻¹ h⁻¹) patients compared with normal-weight (71.0 ± 5.0 nmol·g⁻¹ h⁻¹) and overweight/obese (82.2 ± 8.7 nmol·g⁻¹ h⁻¹) patients, respectively. Palmitate oxidation was negatively (R = –0.44, P = 0.003) associated with BMI. Long-chain fatty acyl-CoA content was higher in both the overweight/obese and extremely obese patients compared with normal-weight patients, despite significantly lower fatty acid oxidation only in the extremely obese. No associations were observed between long-chain fatty acyl-CoA content and palmitate oxidation. These data suggest that there is a defect in skeletal muscle fatty acid oxidation with extreme obesity but not overweight/obesity and that the accumulation of intramyocellular long-chain fatty acyl-CoAs is not solely a result of reduced fatty acid oxidation.

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RESEARCH DESIGN AND METHODS

Human Subjects

Twenty-four females participated in this investigation, which consisted of eight normal-weight [age 45.1 ± 3.1 yr; body mass index (BMI) 23.8 ± 0.58 kg/m²], eight overweight/obese (age 44.0 ± 2.8 yr; BMI 30.2 ± 0.81 kg/m²), and eight extremely obese (age 37.9 ± 3.3 yr; BMI 53.8 ± 3.5 kg/m²) patients undergoing abdominal surgery, primarily gastric bypass and total abdominal hysterectomy. Research participants were categorized into their respective groups on the basis of BMI and the classifications of overweight and obesity set forth by the National Institutes of Health (26). BMI inclusionary criteria for the normal-weight, overweight/obese, and extremely obese subjects were 24.9, 25.0–34.9, and ≥40 kg/m², respectively. The experimental protocol was approved by the East Carolina University Policy and Review Committee on Human Research, and informed consent was obtained from all patients. None of the subjects had any diseases or was taking any medications known to alter carbohydrate or lipid metabolism. All subjects had maintained a constant body mass during the year preceding surgery. After an overnight fast (12–18 h), general anesthesia was initiated with a short-acting barbiturate and maintained with fentanyl and a nitrous oxide-oxygen mixture.

Muscle Strip Incubation

Immediately after surgical removal, the rectus abdominus muscle sample was placed in a sealed container with oxygenated ice-cold Krebs-Henseleit buffer for transport to the laboratory. Muscle strips were incubated in a modified incubation system, as previously described (7). Briefly, muscle strips weighing ~25 mg were teased from the biopsy sample and clamped in lucite clips to maintain consistent resting muscle length and tension throughout the preparation. The clipped muscle strips were immediately placed in 3.0 ml of warmed (30°C) Krebs-Henseleit buffer gassed with 95% O₂-5% CO₂ (pH 7.4) and containing 4% bovine serum albumin (fatty acid free, Sigma Chemical, St. Louis, MO), 5 mM glucose (Sigma Chemical), and 1 mM palmitate (Sigma Chemical). Palmitic acid was dissolved in ethanol, and a final desired palmitate concentration. An overnight fast (12–18 h), general anesthesia was initiated with a short-acting barbiturate and maintained with fentanyl and a nitrous oxide-oxygen mixture.

Extraction of muscle lipids. After their incubation, muscles were blotted and weighed, placed in 13-ml plastic centrifuge tubes containing 1.5 ml of ice-cold 1:2 chloroform-methanol (vol/vol), and homogenized with a polytron (Brinkman Instruments, Mississauga, ON, Canada). An additional 0.5 ml of 100% chloroform was added, and the sample was rehomogenized. Samples were then centrifuged at 2,000 g (4°C) for 10 min, and the chloroform supernatant containing the lipids was transferred to a clean glass tube. Two milliliters of 1:1 chloroform-methanol (vol/vol) were added to the original pellet, which was vortexed and recentrifuged, and the supernatant was added to the previous aliquot. Two milliliters of deionized H₂O were added to the combined supernatants, which were then shaken for 10 min followed by 10 min of centrifugation. The aqueous phase was carefully sampled for the determination of 14C-water-soluble metabolites, and the remainder was aspirated without disturbing the lower chloroform phase. The chloroform phase was transferred to a clean glass tube, gently evaporated under a stream of 100% N₂, and redissolved in 100 µl of 2:1 chloroform-methanol with the addition of phosphatidylcholine, palmitate, and mono-, di-, and tripalmitin (Sigma Chemical). Fifty microliters of each sample were spotted in respective lanes on an oven-dried silica gel plate (Silica Gel GF, 250 μm; Analtech, Newark, DE), and the plates were placed in a sealed tank containing solvent (60:40:3, heptane-isopropl ether-acetic acid) for ~40 min. Plates were air dried for 1 h and placed in a sealed tank containing iodide crystals, which permitted visualization of the bands depicting phospholipids (PL), monoacylglycerols (MG), diacylglycerols (DG), free fatty acids (FFA), and triacylglycerols (TG). The individual lipid bands were marked on the plate and scraped into vials for liquid scintillation counting. Eighty-five to ninety percent of the 14C label incorporated into the lipid pools of the muscle samples was recovered in the PL, MG, DG, FFA, and TG bands. Data are presented for palmitate incorporation into IMTG and the sum of palmitate incorporation into all lipid fractions (TG, DG, FA, MG, and PL), which is referred to as intramyocellular lipid content (IMLC).

Oil Red-O Analyses

Due to the incorporation pattern of [14C]palmitate into IMTG and IMLC, an additional experiment was performed to examine total IMLC (TLC) in a locomotive muscle in a separate set of female subjects. Oil Red-O analysis (30) was performed on vastus lateralis biopsy samples from normal-weight (n = 6, BMI 22.1 ± 0.8 kg/m²), overweight/obese (n = 6, BMI 32.9 ± 0.8 kg/m²), and extremely obese (n = 7, BMI 42.8 ± 0.9 kg/m²) females.

Muscle samples were obtained by biopying the vastus lateralis muscle with a Bergstrom needle and a suction syringe, with subjects under local anesthesia. The biopsy samples were fractioned and prepared for bright-field microscopy and Oil Red-O analyses. Briefly, muscle samples were fixed in 10% buffered Formalin for 24 h followed by a 24-h incubation in 30% sucrose. Samples were mounted in an optimal cutting temperature compound (OCT)-tricaprican gum mixture and frozen in isopentane cooled over liquid N₂.

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Muscle samples were sectioned in 10-μm longitudinal slices and placed in a 60% isopropyl alcohol solution for 1 s followed by a 1-h incubation in Oil Red-O stain. Samples were then briefly (1–3 s) rinsed with 60% isopropyl alcohol and washed for 3 min under running tap water. A counterstain in Harris’s hematoxylin was performed for 5 min, which was followed by a 3-min wash under running tap water, a 3-min wash with lithium chloride, and an additional 5-min tap water wash.

The slides were viewed by utilizing a Nikon Microphot FX microscope (Nikon, Tokyo, Japan) at a magnification of ×10 and quantified with Spot Advanced 3.2.4 (Diagnostic Instruments, Sterling Heights, MI) and Image-Pro Plus 4.1 (Media Cybernetics LP, Silver Spring, MD). Spot Advanced 3.2.4 was used to capture and digitalize images from the light microscopy slides. The images were saved as a tagged image format file (TIFF-32 bit). Image-Pro Plus 4.1 was used to quantify the TLC in the digitalized images. Briefly, the image was magnified to enable viewing of the individual pixels that indicate areas of Oil Red-O staining. By use of a pointer tool, red-stained pixels were highlighted, which initiated an automated program that highlighted other pixels in the image with similar intensity of stain. After this procedure was repeated several times, the image was demagnified to its original size and inspected to see whether all areas of staining had been accounted for. At this time, the image was also inspected to make sure that no extramyocellular lipid or artifacts of staining had been erroneously highlighted. In addition, the total area of skeletal muscle was also determined by utilizing the same procedure.

**Fatty Acyl-CoA Analyses**

From the same rectus abdominus sample in which the incubated samples were obtained, a separate sample (50–100 mg) was fractioned, and all visible fat and/or connective tissue was removed and frozen in liquid N₂ for subsequent analyses. Long-chain fatty acyl-CoAs were extracted from the muscle sample by solid-phase extraction, and 17-carbon CoA was added as an internal standard, as previously described (2, 27). A tandem mass spectrometer API 3000 (Perkin-Elmer Sciex) interfaced with a TurbolonSpray ionization source was used for MS-MS analysis (27). Fatty acyl-CoAs were ionized in a negative electrospray mode, and the transition pairs [M–2H]²⁻/[M–H–80]⁻ were monitored in multiple reaction monitoring mode. Doubly charged ions and corresponding product ions (precursor minus phosphate group) were chosen as a transition pair for multiple-reactions monitoring for quantitation (27). Total long-chain fatty acyl-CoA content was calculated as the sum of the long-chain fatty acyl-CoA species measured.

**Calculations and Statistics**

The absolute quantity of palmitate oxidized (nmol) was determined by measuring the radioactivity (dpm) in vials containing the trapped ¹⁴CO₂ and ¹⁴C-water-soluble metabolites. On the basis of specific activity of labeled palmitate in the incubation medium [i.e., radioactivity (dpm)/total palmitate (nmol)], dpm were converted to total palmitate oxidized. The amount of palmitate incorporated into endogenous lipid pools was calculated in the same manner after the radioactivity in the various lipid fractions was determined. A ratio of palmitate incorporation to palmitate oxidation was utilized to examine differences in skeletal muscle fatty acid partitioning between groups. All data are reported as means ± SE. Results were analyzed using analysis of variance (ANOVA) procedures, and Tukey's post hoc test was used to test significant differences revealed by the ANOVA. Pearson correlational analyses were used to examine associations among palmitate metabolism, subject characteristics, and fatty acyl-CoA content. Significance was accepted at P < 0.05.

**RESULTS**

**Subject Characteristics**

BMI was significantly different among the normal-weight, overweight/obese, and extremely obese subjects. Relative to the normal-weight group, the BMIs for the overweight/obese and extremely obese groups were 27 and 126% higher, respectively. The BMI of the extremely obese group was 78% higher than that of the overweight/obese group.

**Palmitate Oxidation and Incorporation into Muscle Lipids**

Palmitate oxidation and incorporation have been expressed relative to gram tissue wet weight. Previously, our laboratory (7) has shown that intact rectus abdominus muscle strips from normal-weight and extremely obese subjects did not differ in protein, fat, or water content. Thus we are confident that expressing our results relative to gram tissue wet weight provides the same result as would expressing our data relative to milligram protein. Palmitate oxidation (Fig. 1) was 58 (P = 0.011) and 83% (P = 0.001) lower in the extremely obese patients compared with the normal-weight and overweight/obese patients, respectively. No differences in palmitate oxidation were observed between the normal-weight and overweight/obese groups. Palmitate oxidation was negatively associated (P = 0.03, R = −0.44) with BMI.

No statistically significant differences were observed between groups for palmitate incorporation into IMTG or IMLC; however, palmitate incorporation into IMTG was 40% and 37% higher in the extremely obese compared with the normal-weight and overweight/obese patients, respectively. IMLC was 22% higher in the extremely obese compared with the normal-weight and overweight/obese patients, respectively. Palmitate incorporation into IMTG (R = 0.54, P = 0.007)
and IMLC ($R = 0.53$, $P = 0.009$) was significantly correlated with BMI.

The extremely obese patients exhibited a 94 and 105% higher fatty acid partitioning ratio (ratio between incorporation and oxidation) compared with the normal-weight and overweight/obese patients, respectively (Fig. 2). No differences in fatty acid partitioning were observed between the normal-weight and overweight/obese groups.

**Oil Red-O Analyses**

There were no differences in TLC (Fig. 3) between the normal-weight and overweight/obese obese patients. The skeletal muscle from the extremely obese patients contained 224 and 201% more TLC compared with the normal-weight and overweight/obese patients, respectively.

**Long-Chain Fatty Acyl-CoA Analyses**

Long-chain fatty acyl-CoA data are presented in Fig. 4. Concentrations of palmitoyl-CoA (C16:0), oleate-CoA (C18:1), linoleate-CoA (C18:2), and total fatty acyl-CoAs were significantly ($P < 0.05$) higher in both the overweight/obese and extremely obese skeletal muscle compared with normal-weight muscle. Compared with normal-weight skeletal muscle, palmitoleate-CoA (C16:1) was significantly higher only in the extremely obese, and stearoyl-CoA (C18:0) was significantly higher only in the overweight/obese. No significant differences were observed between overweight/obese and extremely obese skeletal muscle for total long-chain fatty acyl-CoAs or any long-chain fatty acyl-CoA subfraction. In addition, there were no associations between palmitate oxidation and incorporation with total long-chain fatty acyl-CoAs or any long-chain fatty acyl-CoA subfraction (data not shown).

**DISCUSSION**

There were two major findings from the present study. 1) In vitro palmitate oxidation is significantly reduced in the skeletal muscle of extremely obese patients; and 2) concentrations of total long-chain fatty acyl-CoAs and long-chain fatty acyl-CoA subfractions were significantly higher in overweight/obese and extremely obese patients compared with normal-weight patients despite a reduction in fatty acid oxidation only in the extremely obese.

The reduced palmitate oxidation observed with extreme obesity in the present study appears to be in conflict with previously reported data (10, 34, 35, 38). Steinberg et al. (34), using an in vitro model very similar to that used in the current investigation, reported no reduction in palmitate oxidation in intact muscle strips from obese women. Also, whole body calorimetry data indicate that the reliance on fat for energy is either greater (10, 38) or not different (35) in obese individuals compared with lean controls. The disparity between the results from the present study and those of others (10, 34, 35, 38) may possibly be explained by the degree of adiposity of the obese subjects investigated. The mean BMI for the overweight/obese and extremely obese groups from the current investigation were 30 and 54 kg/m², respectively, compared with a BMI of 32 kg/m² for the obese group from Steinberg et al. Palmitate oxidation was not different between the overweight/obese and normal-weight skeletal muscle in the present study, which is in agreement with Steinberg et al. The obese groups examined in whole body calorimetry studies (10, 35, 38) were very similar, with respect to adiposity, to the obese group.

**Fig. 2.** Fatty acid partitioning (ratio of palmitate incorporation to palmitate oxidized) in rectus abdominus strips from normal-weight, overweight/obese, and extremely obese females. Data are expressed as means ± SE. *Extremely obese have a significantly higher partitioning ratio ($P < 0.05$) compared with the normal weight and overweight/obese.

**Fig. 3.** Intramyocellular lipid content in vastus lateralis based on Oil Red-O analyses. Data are expressed as means ± SE. *Extremely obese have statistically ($P < 0.05$) greater total intramyocellular lipid content than the normal weight and overweight/obese.

**Fig. 4.** Fatty Acyl-CoA concentrations: palmitoyl-CoA (C16:0), palmitoleate (C16:1), stearoyl-CoA (C18:0), oleate-CoA (C18:1), linoleate-CoA (C18:2). Data are expressed as means ± SE. *Statistically different ($P < 0.05$) from normal weight. No differences were observed between overweight/obese and extremely obese.
from Steinberg et al. and the overweight/obese group from the present study. Thus it is not our intention to 
dispute the results of previous investigations (10, 34, 
35, 38), as the data from the current study support the 
findings of no defect in fatty acid oxidation with mod-
erate obesity; however, we have demonstrated that fatty acid oxidation is reduced with extreme obesity. A 
previous study from our laboratory (22) provides addi-
tional support for reduced fatty acid oxidation with 
 extreme obesity but not moderate obesity. Kim et al. 
(22) examined fatty acid oxidation in vastus lateralis 
muscle homogenates in lean (BMI 23.8 kg/m²) and 
obese (BMI 38 kg/m²) women and observed an ~100% 
 reduction (P < 0.05) in fatty acid oxidation with obe-
sity. However, when the subjects (see Fig. 2A in Ref. 
22) were divided into normal-weight (BMI < 24.9 kg/ 
m²), overweight/obese (BMI 25–35 kg/m²), and 
extremely obese (BMI > 35 kg/m²) groups, fatty acid oxida-
tion was not different between the normal-weight 
and overweight/obese groups but was 276% lower in 
the extremely obese. Together, our data (present study 
and Kim et al.) and those of others (10, 33, 35, 38) 
suggest that fatty acid oxidation is lower in skeletal 
muscle of extremely obese, but not moderately obese 
individuals.

A potential mechanism for the reduction in fatty acid 
oxidation with extreme obesity may be a blunted ox-
idative capacity. This notion is supported by previous 
work from our laboratory (22) in which two enzymes 
known to be rate-limiting steps in fatty acid oxidation 
(β-hydroxyacyl dehydrogenase and citrate synthase) 
were demonstrated to have significantly lower activity 
in rectus abdominus muscle tissue from extremely 
 obese subjects compared with normal-weight controls. 
In addition, the activity of carnitine palmitoyltrans-
ferase I, which is a rate-limiting step for entry of fatty 
acyl-CoAs into the mitochondria for oxidation, was also 
significantly lower in extremely obese skeletal muscle 
compared with nonobese controls (21). Furthermore, 
Hickey et al. (18) demonstrated that the percentage of 
type I muscle fibers in rectus abdominus tissue was 
significantly lower in extremely obese compared with 
normal-weight subjects. Thus it appears that the re-
duction in fatty acid oxidation observed with extreme 
obesity may be due, at least in part, to a decrement in 
skeletal muscle oxidative capacity.

The accumulation of IMTG is associated with skele-
tal muscle insulin resistance (3, 13, 15, 19, 23, 28, 29, 
31, 36, 39). Kelly and Goodpaster (20) have proposed 
that the accumulation of TG within obese skeletal 
muscle is due to a defect in fatty acid oxidation. The 
findings from the present investigation demonstrate 
that, in the presence of reduced skeletal muscle fatty 
acid oxidation in extremely obese patients, there was a 
trend for greater (37–40%) palmitate incorporation 
into IMTG compared with the normal-weight and 
overweight/obese patients. Furthermore, using Oil Red-O 
analyses in a separate set of female subjects, we ob-
erved significantly greater IMLC in vastus lateralis 
muscle tissue from extremely obese patients compared 
with normal-weight and overweight/obese patients. In 
addition, we examined the ratio of palmitate incorpo-
ration to palmitate oxidation in an effort to determine 
whether extremely obese patients preferentially parti-
tion fatty acids toward storage and away from oxida-
tion. The ratio was 95–105% higher in the extremely 
obese patients relative to the normal-weight and over-
weight/obese patients. Our data support the hypothe-
sis that a defect in skeletal muscle fatty acid oxidation 
may result in the accumulation of IMTG. Little work 
had been done to examine TG synthesis and hydrolysis 
in skeletal muscle with human obesity. The possibility 
exists that not only is fatty acid oxidation reduced, but 
perhaps TG synthesis and hydrolysis are upregulated 
and downregulated, respectively, with extreme obesity.

The accumulation of IMTG is not believed to be the 
direct cause of the development of insulin resistance 
but more of a marker for the presence of other lipid 
intermediates, which have been directly linked to de-
fects in insulin signaling (8, 17, 25, 32, 37). Intramy-
ocellular long-chain fatty acyl-CoA accumulation has 
been implicated in the pathogenesis of insulin resis-
tance in skeletal muscle (4, 8, 32, 37). A potential 
mechanism for the accumulation of long-chain fatty 
acyl-CoAs in skeletal muscle may be reduced fatty acid 
oxidation. In the current investigation, we examined 
the content of total long-chain fatty acyl-CoAs and 
long-chain fatty acyl-CoA subfractions in the same 
muscle tissue in which we examined palmitate oxida-
tion. Our results do not support the notion that long-
chain fatty acyl-CoA accumulation in skeletal muscle is 
due solely to a reduction in fatty acid oxidation. Long-
chain fatty acyl-CoA content was higher in both the 
overweight/obese and extremely obese patients 
compared with normal-weight patients despite signifi-
cantly lower fatty acid oxidation only in the extremely 
obese. In addition, no associations were observed be-
tween long-chain fatty acyl-CoA content and palmitate 
oxidation. Thus the accumulation of intramyocellular 
long-chain fatty acyl-CoAs with obesity appears to be 
due to other, yet to be defined, mechanisms.

The present study is the first, to our knowledge, to 
report intramyocellular concentration of long-chain 
fatty acyl-CoAs in human subjects of varying degrees 
of adiposity. We observed higher long-chain fatty acyl-
CoA accumulation in the skeletal muscle of over-
weight/obese and extremely obese subjects compared 
with normal-weight subjects. These findings match 
very nicely with previously reported data from our 
laboratory in which we established the presence of 
insulin resistance in moderately and extremely obese 
populations (1, 6, 7, 9). In addition, it appears that 
insulin resistance increases linearly with the progres-
sion of obesity up to a BMI of ~30 kg/m²; however, 
above this threshold there is no further progression of 
insulin resistance with increases in BMI (1, 9). As 
stated previously, intramyocellular long-chain fatty 
acyl-CoA accumulation has been implicated in the 
pathogenesis of insulin resistance in skeletal muscle 
(4, 8, 32, 37). More specifically, this intermediate of 
fatty acid metabolism can have direct effects on glucose 
utilization by altering enzyme activity and/or inhibit-
ing key components of the insulin-signaling pathway (4, 32). Thus our findings with long-chain fatty acyl-CoA concentrations may provide a mechanistic explanation as to why insulin resistance develops with the progression from normal weight to moderately obese but not with further increases in adiposity.

A decreased reliance on lipids as an energy source has previously been identified as a metabolic risk factor for weight gain (40). In addition, Kelley et al. (21) suggested that impairment in skeletal muscle fatty acid oxidation might be a predisposing factor contributing to the development of obesity as well as weight regain following weight loss. Furthermore, recent data from our laboratory (16) demonstrated the persistence of reduced fatty acid oxidation during exercise in formerly extremely obese patients after weight loss compared with controls matched for age, race, and BMI. These findings indicate that, even in a weight-reduced state, formerly extremely obese women demonstrate a defect in the ability to utilize fat for energy and thus provide additional support for the theory that defective lipid oxidation may predispose individuals to extreme obesity.

In summary, the findings from the current investigation indicate a defect in skeletal muscle fatty acid oxidation with extreme obesity but not with overweight/obese subjects. On the basis of these data, we hypothesize that extreme obesity may be due, in part, to inherent defects in skeletal muscle lipid metabolism. It is important to discern the cellular mechanisms that may contribute to extreme obesity, as extremely obese individuals comprise ~5% of the population and contribute significantly to health care costs (12). In addition, on the basis of the results of this study, the accumulation of intramyocellular long-chain fatty acyl-CoAs does not appear to be a result of defective lipid oxidation. Thus the accumulation of long-chain fatty acyl-CoAs implicated in the pathogenesis of insulin resistance in obese skeletal muscle must be due to some other, yet to be defined, mechanism.

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