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Resting and Exercise Energy Metabolism in Weight-Reduced Adults with Severe Obesity

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Abstract

Objective: To determine effects of physical activity (PA) with diet-induced weight loss on energy metabolism in adults with severe obesity.

Methods: Adults with severe obesity (n=11) were studied across 6mo of intervention, then compared to controls with less severe obesity (n=7) or normal weight (n=9). Indirect calorimetry measured energy metabolism during exercise and rest. Markers of muscle oxidation were determined by immunohistochemistry. Data are presented as medians.

Results: The intervention induced 7% weight loss (p=0.001) and increased vigorous PA by 24min/wk (p=0.02). During exercise, energy expenditure (EE) decreased, efficiency increased (p 0.03), and fatty acid oxidation (FAO) did not change. Succinate dehydrogenase (SDH) increased (p=0.001), but fiber type remained the same. Post-intervention subjects' resting metabolism remained similar to controls. Efficiency was lower in post-intervention subjects compared to normal weight controls exercising at 25W (p 0.002) and compared to all controls exercising at 60% VO_{2peak} (p 0.019). Resting and exercise FAO of post-intervention subjects

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remained similar to adults with less severe obesity. SDH and fiber type were similar across all body weight statuses.

Conclusions: While metabolic adaptations to PA during weight loss occur in adults with severe obesity, FAO does not change. Resulting FAO during rest and exercise remains similar to adults with less severe obesity.

Keywords

severe obesity; fat metabolism; work efficiency; lifestyle intervention

Introduction

Obesity continues to increase in prevalence¹ and severity; over 15% of the adult population in the United States has the highest classification of obesity (i.e. class 2 and 3; body mass index [BMI] ≥ 35 kg/m²)². One initial strategy for treatment is a lifestyle intervention³. Advantages of incorporating physical activity with dietary changes include additional weight loss and health benefits^{3,4}.

Adaptations to physical activity have commonly been examined in adults of normal weight. Training adaptations include improvements in work efficiency - the amount of work achieved relative to energy expended⁵⁻⁷. There are also changes in the energy source as demonstrated by increased fatty acid oxidation during low and moderate intensity exercise^{8,9}, as well as during rest¹⁰. A small number of studies examined how increased physical activity combined with caloric restriction impacts work efficiency, rates of oxygen consumption (VO₂), energy expenditure (EE), and/or substrate utilization during exercise in adults who are overweight or obese^{5-7,11-15}. Although changes in substrate utilization during exercise are common in adults with normal weight, this is not a consistent finding in adults who are overweight or obese during exercise^{5-7,11-14} or at rest^{6,7,11,14}. To date, there are no reports of changes in these parameters of energy metabolism during exercise in adults with severe obesity who completed exercise training during diet-induced weight loss.

Furthermore, the mechanism behind metabolic adaptations to exercise has yet to be fully elucidated. Skeletal muscle significantly contributes to VO₂, EE and fatty acid oxidation during exercise. With endurance training, there is a shift towards myofibers with an oxidative phenotype (type I fibers)¹⁶ and/or increased mitochondria content and function to allow for enhanced oxidative capacity¹⁷⁻¹⁹. These adaptations occur in previously sedentary adults with normal weight, but it is unknown whether adults with severe obesity respond in a similar manner, especially when exercise is combined with weight loss.

The current study examined how physical activity incorporated into a weight loss intervention affected work efficiency, as well as VO₂, EE and fatty acid oxidation during exercise and rest in adults with severe obesity. Given the differences in whole-body and skeletal muscle metabolism of adults with severe obesity compared to other BMI classifications²⁰⁻²⁶, we compared how the resulting energy metabolism in post-intervention adults with severe obesity compared to adults with less severe obesity (i.e. class 1), as well as the typical reference group (i.e. adults with normal weight). We hypothesized that the

lifestyle intervention in adults with severe obesity would improve work efficiency, VO_2 and EE without changing substrate utilization when completing exercise. Any changes in these parameters of energy metabolism in adults with severe obesity would be comparable to adults with less severe obesity, but not those of normal weight.

Methods

The Institutional Review Board of the University of Pittsburgh approved the protocol, and volunteers provided written informed consent to participate. The study is registered at: <https://clinicaltrials.gov/show/NCT00712127>.

Subjects.

Males and females aged 30–55 yr with severe obesity ($\text{BMI} \geq 35.0 \text{ kg/m}^2$) were enrolled in a randomized clinical trial of lifestyle interventions consisting of a yearlong diet and/or progressive physical activity program as previously detailed⁴. Participants were assumed to be sedentary. We aimed to enroll at least 9 participants to provide 80% power to detect a difference in fatty acid oxidation as a result of lifestyle interventions in adults with severe obesity. Eleven of the participants randomized to the “initial activity intervention” group (i.e. physical activity and diet) in the parent study agreed to concurrently participate in this substudy.

Controls were matched to intervention participants by sex, race/ethnicity and age, but were differentiated by BMI. These volunteers were to have BMI classifications of either class 1 obesity ($\text{BMI}: 30.0\text{--}34.9 \text{ kg/m}^2$) or normal weight ($\text{BMI}: 20.0\text{--}24.9 \text{ kg/m}^2$). To match for sedentary lifestyle, volunteers could not regularly participate in purposeful exercise $> 2 \text{ d/wk}$. Additionally, the inclusion and exclusion criteria for the parent study were applied to controls⁴.

Protocol.

The following assessments were completed at baseline (weeks $-4\text{--}0$) and after 6 mo of intervention (weeks 24–28; referred to as post-intervention) in the group with severe obesity. The control groups completed the assessments at only one timepoint (referred to as baseline).

Body Composition Analysis.—Dual-energy x-ray absorptiometry (General Electric Lunar prodigy scanner with EnCore software 2005, Madison, WI) determined fat-free mass (FFM), fat mass and percent body fat.

Objectively-measured Physical Activity.—A multisensory activity monitor (SenseWear Pro3, BodyMedia, Pittsburgh, PA) assessed free-living physical activity as previously detailed^{4,27}. The accompanying software (Innerview Software, BodyMedia, Pittsburgh, PA) analyzed time spent in physical activity of at least moderate (≥ 3.0 metabolic equivalents, MET) and vigorous intensities (≥ 6.0 MET).

Aerobic Exercise Capacity Assessment.—All participants performed a graded exercise test using a modified Balke protocol on a cycle ergometer (Excalibur, Lode, The

Netherlands) to determine peak aerobic capacity ($\text{VO}_{2\text{peak}}$) by indirect calorimetry (Moxus, AEI Technologies, Naperville, IL) at baseline.

Skeletal Muscle Analyses.—Markers of skeletal muscle oxidative capacity, including fiber type distribution and succinate dehydrogenase (SDH), were measured in percutaneous muscle biopsy samples as previously described^{20,28}.

Whole-body Metabolism Analyses.—After an overnight fast, expired air was collected to measure rates of oxygen consumption (VO_2 , ml/min) and carbon dioxide production (VCO_2 , ml/min) by indirect calorimetry during rest as previously described²⁷, and during submaximal exercise bouts. At least 1 wk after the $\text{VO}_{2\text{peak}}$ assessment, participants completed submaximal exercise on the cycle ergometer; the first 10 min were performed at an absolute workload of 25 W, and the consecutive 10 min were performed at a relative workload equivalent to 60% of $\text{VO}_{2\text{peak}}$. Post-intervention the workloads for the submaximal exercise were the same as baseline so that the two consecutive bouts were set at absolute workloads. Expired air was collected from minutes 3–5, 8–15 and 18–20 to confirm steady-state and that the appropriate workloads were achieved. The last 2 min of each workload were used in the calculations below. In addition, these participants replicated the percentage of macronutrient content of a 3 d food record completed prior to the baseline submaximal exercise test. This step was taken in an attempt to control for effects of macronutrient content on substrate oxidation.

Calculations.—In addition to respiratory exchange ratio (RER; VCO_2/VO_2), the following equations adopted from Frayn²⁹ calculated whole-body fatty acid oxidation and EE from indirect calorimetry measures:

$$\text{fatty acid oxidation} = 1.67\text{VO}_2 - 1.67\text{VCO}_2$$

$$\text{EE} = \text{fatty acid oxidation} + (4.55\text{VCO}_2 - 3.22\text{VO}_2)$$

Fatty acid oxidation was expressed as g/min and percentage of EE derived from fatty acids (%). EE was expressed as kcal/d at rest and kcal/min during exercise, and was also expressed per kg of FFM.

Work efficiency, expressed as gross and net efficiency, was calculated using the following equations³⁰:

$$\text{gross efficiency} = \text{work} \div \text{EE} \times 100$$

$$\text{net efficiency} = \text{work} \div (\text{EE} - \text{resting EE}) \times 100$$

Statistical Analysis.

Data were not normally distributed, thus continuous variables were expressed as medians with percentiles (25th, 75th). Categorical variables were summarized with frequencies and percentages. The Wilcoxon signed-rank test assessed statistical significance of differences between baseline and post-intervention measurements of BMI, body composition parameters, objectively-measured physical activity, variables of whole-body energy

metabolism and markers of muscle oxidative capacity at $p = 0.05$. Spearman's rank correlations tested associations between changes in parameters of body composition (i.e. FFM, fat mass and percent body fat), and objectively-measured physical activity of at least moderate and vigorous intensities, to changes in work efficiency with intervention. Analyses of variance and chi square tests confirmed matching of sex, race/ethnicity, age and objectively-measured physical activity across the adults with severe obesity, class 1 obesity and normal weight. Comparisons of whole-body energy metabolism and markers of muscle oxidative capacity between post-intervention adults and control groups were analyzed with Kruskal-Wallis one-way analysis of variance. When the overall comparison indicated a statistically significant difference ($p = 0.05$), pairwise comparisons were made between post-intervention adults and each control group; a Bonferroni adjustment corrected for multiple comparisons to detect statistically significant differences at $p = 0.025$ ($0.05/2$ comparisons). Analyses were conducted using JMP version 10.0.0 (SAS Institute, Cary, NC).

Results

Characteristics of Adults with Severe Obesity Across Intervention.

Table 1 presents the characteristics of the 11 adults with severe obesity. Time spent in physical activity of at least moderate intensity had a median increase of 164 min/wk ($-202, 341$; $p=0.41$), while vigorous physical activity had a median increase of 24 min/wk ($17, 82$; $p=0.02$). The intervention induced a median change in body weight of -7% ($-11, -4$; $p=0.001$), including decreases in fat mass (kg, $p=0.002$; %, $p=0.01$) and FFM ($p=0.007$). Despite a median decrease in BMI of 3.0 kg/m^2 ($1.5, 5.2$; $p=0.001$) with intervention, all participants continued to be classified as severely obese.

Characteristics of Groups.

Table 1 also presents the comparison between post-intervention adults with severe obesity to controls with class 1 obesity ($n=7$) and normal weight ($n=9$). By study design, sex ($p=0.49$) and age ($p=0.25$) were similar between groups, and BMI was different between groups ($p<0.0001$). Although we aimed to also match by race/ethnicity, there was a difference across groups ($p=0.02$). When race was a significant covariate in the statistical analysis, the results were presented. Objectively-measured physical activity of at least moderate intensity ($p=0.26$) and absolute $\text{VO}_{2\text{peak}}$ (ml/min) were similar across groups ($p=0.23$), but $\text{VO}_{2\text{peak}}$ expressed relative to FFM was not ($p=0.0005$).

Oxidative Capacity in Skeletal Muscle.

Baseline muscle fiber distribution has previously been reported in these participants²⁰. Adults with severe obesity had no change in proportion of type 1 muscle fiber ($p=0.70$; Figure 1), but increased SDH with intervention ($p=0.001$; Figure 2).

Post-intervention adults with severe obesity had similar type 1 fiber ($p=0.46$) and SDH ($p=0.20$) compared to controls (Figures 1 and 2).

Whole-body Energy Metabolism at Rest.

With intervention, the median decrease in resting EE of adults with severe obesity was 203 kcal/d (49, 256; $p=0.04$), which was not a significant change when expressed relative to FFM ($p=0.24$). There were no changes in resting fatty acid oxidation with intervention (expressed as RER, mg/min or %; $p=0.18$ for all). Resting EE (kcal/d) was different across groups ($p=0.0002$); post-intervention adults with severe obesity had greater resting EE than adults with class 1 obesity ($p=0.0112$) and normal weight ($p=0.0002$). When expressed per FFM though, EE was not different across groups ($p=0.13$). Whole-body fatty acid oxidation ($p=0.11$ when expressed as RER, mg/min or %) was similar across groups at rest (Table 2).

Whole-body Energy Metabolism during Submaximal Exercise.

During exercise at the absolute, submaximal workload of 25 W, there were decreases in VO_2 ($p=0.03$) and EE (kcal/min; $p=0.03$) with intervention in adults with severe obesity. The change in EE was not significant when expressed relative to FFM ($p=0.07$). The decreases in VO_2 and EE coincided with complementary increases in gross and net efficiencies ($p=0.03$ for all). There was no change with intervention in whole-body fatty acid oxidation ($p=0.05$ when expressed as RER, mg/min or %). During the relative workload, the intervention in adults with severe obesity also resulted in decreases in VO_2 ($p=0.005$) and EE (kcal/min, $p=0.005$; kcal/min/kgFFM, $p=0.04$); these changes occurred concurrently with significant increases in gross and net efficiencies ($p<0.05$ for all), and no change in whole-body fatty acid oxidation ($p=0.10$ when expressed as RER, mg/min or %; Table 2).

We examined which changes in parameters of body composition and objectively-measured physical activity were correlated with improved work efficiency with intervention in adults with severe obesity. The change in body weight was strongly correlated to the change in gross efficiency at the absolute workload ($\rho=-0.68$, $p=0.04$), but only approached significance when related to the change in net efficiency ($\rho=-0.62$, $p=0.08$). At the relative workload, there were strong, negative correlations with the change in body weight to the change in gross and net efficiencies ($\rho=-0.80$, $p=0.003$ and $\rho=-0.72$, $p=0.01$, respectively). No associations were seen between changes in FFM, or objectively-measured physical activity of different intensities, and changes in work efficiency ($p=0.05$ for all).

Table 2 presents the comparison of post-intervention adults with severe obesity to control groups. There were differences across groups in regards to VO_2 ($p=0.0009$) and absolute EE (kcal/min; $p=0.002$) during submaximal exercise at 25 W, but no difference in relative EE (kcal/min/kgFFM; $p=0.28$). Both gross ($p=0.002$) and net efficiencies ($p=0.005$) were also different across groups. Post-intervention adults with severe obesity had lower VO_2 and expended more kcal/min than controls with normal weight, corresponding with lower gross and net efficiencies ($p<0.025$ for all). On the other hand, VO_2 , EE (kcal/min and kcal/min/kgFFM) and work efficiency (gross and net) were similar between the post-intervention adults with severe obesity and controls with class 1 obesity ($p>0.025$ for all). Expressions of whole-body fatty acid oxidation were not different across groups ($p=0.08$ when expressed as RER, mg/min or %).

During the relative workload, there were differences across the groups in VO_2 ($p=0.03$) and EE (kcal/min, $p=0.02$; kcal/min/kgFFM, $p=0.0001$). Post-intervention adults with severe obesity had lower VO_2 ($p=0.0235$) and EE (kcal/min, $p=0.019$; kcal/min/kgFFM, $p=0.0006$) compared to adults with class 1 obesity. Post-intervention adults with severe obesity had similar VO_2 and EE compared to adults of normal weight ($p=0.06$ for both), but EE relative to FFM was lower ($p=0.0004$). There were also differences across groups in gross ($p=0.001$) and net efficiencies ($p=0.005$) during this submaximal exercise bout. Post-intervention adults with severe obesity had lower gross and net efficiencies compared to adults of class 1 obesity and normal weight ($p<0.025$ for all). The deviation from the inverse relationship between VO_2 or EE and work efficiency in the comparison between post-intervention adults with severe obesity and controls can be explained by the power output each participant generated to reach 60% of their $\text{VO}_{2\text{peak}}$. The post-intervention adults with severe obesity completed the exercise bout at a higher VO_2 and lower power output (47; 25, 55 W) compared to controls of normal weight (74; 61, 95 W) and class 1 obesity (78; 70, 90 W). With regards to whole-body fatty acid oxidation, there was a difference across groups in RER ($p=0.02$) and the percentage of EE derived from fatty acids ($p=0.02$). Pairwise comparisons revealed that post-intervention adults with severe obesity had greater fatty acid oxidation, as evidenced by lower RER ($p=0.015$) and greater percentage of EE derived from fatty acids ($p=0.023$), compared to adults with normal weight, but were similar to adults with class I obesity ($p=0.030$ for both). Absolute fatty acid oxidation (mg/min) was not different across groups ($p=0.13$; Table 2).

Discussion

Weight loss due to caloric restriction and increased physical activity in adults with normal weight and obesity improved work efficiency as measured by indirect calorimetry during submaximal exercise^{5,6} and magnetic resonance spectroscopy⁷. Increased work efficiency occurred concomitant with decreased VO_2 and EE, but not necessarily increased fatty acid oxidation⁵⁻⁷. EE at rest also decreased with weight loss^{7,31-33}. These investigations of diet and/or exercise induced changes in energy metabolism have not focused on adults with severe obesity. Our study showed for the first time that adults with severe obesity have whole-body metabolic adaptations to lifestyle interventions that are similar to previous interventions implemented in adults with weight statuses ranging from normal weight to less severe obesity. Our primary finding was that a 6 mo intervention, resulting in ~7% weight loss and increased time spent in weekly vigorous physical activity, increased gross and net efficiencies and decreased VO_2 and EE without compensatory increases in whole-body fatty acid oxidation during submaximal exercise bouts. The same trends in EE and fatty acid oxidation were observed at rest. The post-intervention adults with severe obesity had similar whole-body and skeletal muscle fatty acid oxidation during both metabolic challenges compared to counterparts with less severe obesity. They also had similar fatty acid oxidation to adults of normal weight, but only during rest and the lightest, submaximal exercise workload (i.e. 25 W).

We examined how changes with intervention in body composition parameters could explain our observations in energy metabolism in adults with severe obesity. Although decreased body weight was the only parameter significantly related to increased work efficiency in the

current study and others⁶, this association does not translate to causation. Inducing weight loss by caloric restriction alone does not result in changes in work efficiency, EE or substrate utilization during submaximal exercise bouts⁵. Furthermore, if the body mass lost is artificially replaced, improvements in work efficiency and decreases in VO_2 and EE are maintained at submaximal workloads⁷.

Changes within components of body weight may account for changes in energy metabolism. Previous work from our lab³¹ and others^{32,34} have noted that changes in body composition parameters account for changes in resting EE after weight loss. In particular, FFM accounts for 44 to 77% of resting EE in adults with normal weight and class 1 obesity^{32,34}. Among the larger number of adults with severe obesity enrolled in the parent study, we found that changes with intervention in FFM significantly accounted for 5 to 17% of the change in resting EE, depending on which parameters were included in the regression models³¹. In the current study, however, adjusting resting EE for FFM significantly attenuated or eliminated these intervention effects. During activity above rest, skeletal muscle is the primary tissue energetically activated; thus, we expected that changes in quantity and quality of this tissue would also relate to changes in energy metabolism during exercise. Decreased FFM and increased SDH occurred concurrently with decreased EE and increased work efficiency during submaximal exercise. These changes in skeletal muscle did not account for all changes in energy metabolism with intervention; adjusting EE for FFM did not completely account for the decrease in EE during submaximal exercise in adults with severe obesity, nor did the decrease in FFM and increase in SDH relate to changes in whole-body fatty acid oxidation during exercise.

Given that adults with severe obesity have been shown to have dysfunctional fatty acid oxidation^{20–25}, we contemplated as to whether the lack of a shift in fatty acid oxidation was an inherent metabolic profile that did not adapt to changes in body composition parameters and physical activity. The results of the cross sectional comparisons, however, revealed that whole-body fatty acid oxidation of weight-reduced adults with severe obesity was no different than that of sedentary counterparts with class I obesity, and was often no different than adults of normal weight (Table 2). Additionally, markers of skeletal muscle oxidative capacity were similar across BMI classification groups. Figures 1 and 2, as well as the analysis presented in Figure 3, support that whole-body and skeletal muscle energy metabolism were no different across BMI classification groups that include adults with severe obesity. However, there were differences in work efficiency during submaximal exercise and $\text{VO}_{2\text{peak}}$ (ml/min/kgFFM) between adults with severe obesity and their counterparts (Tables 1 and 2). These findings suggest that the metabolic profile might not be an inherent function of substrate utilization, but rather physiological functions regulating $\text{VO}_{2\text{peak}}$ and work efficiency such as those necessary to sustain repeated muscle contraction during exercise. Interpretation of our findings is limited to examining effects of physical activity and diet-induced weight loss on changes in skeletal muscle mass, SDH content and distribution of type 1 fibers. Other muscular adaptations to exercise training include neural activation of muscles to contract and generate the power needed to complete a given workload³⁵. In particular, increased recruitment of type 1 muscle fibers results in improved work efficiency³⁵. Measures of neuromuscular activation such as electromyographic activity of muscles or voluntary activation of motor units were not included in this study.

Careful consideration needs to be taken in regards to relating statistical significance in our dataset to clinical significance. For example, at baseline, half of adults with severe obesity expended 5 kcal/min or less to complete an absolute submaximal workload, equating to ~100 kcal expended over 20 min. Following the intervention, half of adults with severe obesity expended 4 kcal/min or less at the same workload, resulting in ~80 kcal expenditure over 20 min. While the change in EE was statistically significant, it is not clear whether the decrease of 20 kcal expended during exercise would substantially contribute to the overall energy deficit for weight loss.

In conclusion, a lifestyle intervention that induces weight loss with caloric restriction and increases physical activity reduced EE during rest and submaximal exercise, and enhanced work efficiency in adults with severe obesity. These metabolic adaptations were observed in conjunction with increased oxidative enzyme content within skeletal muscle, but not changes in muscle fiber type distribution or altered whole-body fatty acid oxidation. The resultant whole-body and skeletal muscle energy metabolism in adults with severe obesity was similar to adults with less severe obesity and normal weight at rest. Even during submaximal exercise workloads, fatty acid oxidation remained similar to adults with less severe obesity. Fatty acid oxidation even remained similar to adults of normal weight during the lightest workload of 25 W, despite lower efficiency. This enhanced energy metabolism may require greater EE during active weight loss to maintain energy deficit or energy balance. Future studies should consider whether these metabolic adaptations are associated with weight regain or weight loss maintenance in adults with severe obesity.

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What is already known about this subject?

- Previously sedentary adults with normal weight involved in exercise training programs improve work efficiency with decreased energy expenditure and increased fatty acid oxidation during submaximal exercise bouts, as well as during resting conditions.
- These adaptations parallel changes in muscle structure and function, including fiber type distribution and mitochondrial content and function.
- Increased physical activity with diet-induced weight loss also improves work efficiency with decreased energy expenditure during exercise in adults with normal weight and class 1 obesity.

What does your study add?

- This study provides evidence that metabolic adaptations to exercise can also occur in a population typically excluded from research studies - adults with severe obesity. Participants assigned to a lifestyle intervention consisting of physical activity and a calorie-restricted diet improved work efficiency and decreased energy expenditure during submaximal exercise bouts.
- Improved work efficiency and decreased energy expenditure during submaximal exercise were strongly associated with the amount of weight lost with intervention, but were not related to changes in muscle, include muscle mass or markers of muscle oxidative capacity.
- Six months after a lifestyle intervention, weight-reduced adults with severe obesity had similar whole-body and skeletal muscle energy metabolism at rest and during submaximal exercise as their counterparts of normal weight and class I obesity, suggesting the importance of including a progressive physical activity regimen for continued weight loss and/or maintenance of reduced body weight.

FIGURE 1. Percentage of type 1 fibers in skeletal muscle.

Type 1 fibers of adults with severe obesity did not change from baseline to post-intervention ($n = 11$; $p=0.70$). There was no difference between post-intervention adults with severe obesity, and adults of class 1 obesity ($n=7$) and normal weight ($n=9$; $p=0.46$). The box plots depict the group medians (identified by a line inside the box) and values for the 25th and 75th percentiles.

FIGURE 2. Succinate Dehydrogenase (SDH) in skeletal muscle.

SDH content in adults with severe obesity (n=11) increased from baseline to post-intervention (*p=0.001). There was no difference between post-intervention adults with severe obesity and controls of normal weight (n=9) and class 1 obesity (n=7; p=0.20). The box plots depict the group medians (identified by a line inside the box) and values for the 25th and 75th percentiles.

FIGURE 3. Whole-body fatty acid oxidation in weight-reduced adults with severe obesity and counterparts with lower body mass index (BMI) as a function of BMI.

Rates of whole-body fatty acid oxidation at rest (A) and during exercise bouts performed at 25 W (B) and 60% of $\text{VO}_{2\text{peak}}$ (C) across the BMI of adults with normal weight, class 1 obesity and post-intervention adults with severe obesity. Results from Spearman's correlations are presented.

TABLE 1

Characteristics of participants in each group, including baseline and post-intervention results of the adults with severe obesity. Data are presented as medians and 25th and 75th percentiles unless otherwise noted.

	Adults with Severe Obesity		Control Groups		P-values	
	Baseline (n=11)	Post-intervention (n=11)	Class 1 Obese (n=7)	Normal Weight (n=9)	Baseline vs. Post-intervention	Across Groups ^a
Female n (%)	9 (82)	–	7 (100)	8 (89)	–	NS 0.49
Caucasian n (%)	4 (36)	–	6 (86)	8 (89)	–	0.02
Age (yr)	47 (43, 49)	–	48 (46, 54)	46 (34, 50)	–	NS 0.25
Height (cm)	163.6 (161.4, 173.5)	–	160.9 (159.2, 169.6)	162.7 (159.7, 173.5)	–	–
Weight (kg)	122.3 (111.7, 126.3)	110.0 (103.4, 119.7)	84.4 (80.4, 92.4)	61.8 (58.3, 66.2)	0.001	–
BMI (kg/m ²)	43.6 (38.4, 47.1)	38.0 (36.1, 43.3)	32.1 (31.1, 33.0)	22.6 (21.4, 23.7)	0.001	<0.0001
Fat Free Mass (kg)	58.4 (54.2, 62.6)	57.2 (51.6, 60.0)	43.7 (41.3, 49.5)	37.1 (35.7, 46.0)	0.007	–
Fat Mass (kg)	58.0 (55.1, 63.6)	49.5 (42.5, 55.5)	35.6 (33.5, 39.8)	18.8 (16.5, 21.2)	0.002	–
Body Fat (%)	50.8 (45.3, 53.2)	45.9 (41.8, 51.8)	42.4 (42.1, 45.2)	32.0 (25.9, 35.4)	0.01	–
Physical Activity (min/wk)	562 (191, 883)	591 (476, 831)	707 (531, 1030)	818 (581, 1422)	NS 0.41	NS 0.26
VO _{2peak} (ml/min)	2084 (1801, 2202)	–	2236 (2129, 2446)	1964 (1722, 2468)	–	NS 0.23
VO _{2peak} (ml/min/kgFFM)	35.9 (31.8, 40.4)	–	52.4 (50.7, 53.7)	50.2 (47.3, 53.6)	–	0.0005

^a Matching confirmation across groups includes adults with severe obesity at baseline and controls

TABLE 2

Median and 25th and 75th percentiles of energy expenditure (EE), fatty acid oxidation (respiratory exchange ratio, RER; mg/min; and percentage of energy derived from fatty acids, %) and work efficiency, are presented for adults with severe obesity at baseline and post-intervention, as well as controls, during rest and two submaximal exercise workloads.

	Adults with Severe Obesity			Control Groups		P-values		Adjusted P-values ^c	
	Baseline	Post-intervention		Class 1 Obese	Normal Weight	Baseline vs. Post-intervention ^a	Across Groups ^b	Post-intervention vs. Class 1 Obese	Post-intervention vs. Normal Weight
Rest	(n=11)	(n=11)		(n=7)	(n=9)				
EE (kcal/d/kgFFM)	1913 (1765, 1956)	1642 1642 (1594, 1770)		1495 1495 (1345, 1620)	1376 1376 (1210, 1478)	0.04	0.0002	0.0112	0.0002
EE (kcal/d/kgFFM)	31.0 (29.4, 36.0)	30.3 (28.7, 31.5)		30.8 (30.2, 37.2)	34.8 (29.8, 37.6)	Not Significant 0.24	Not Significant 0.13	N/A	N/A
Fatty Acid Oxidation (RER)	0.78 (0.77, 0.80)	0.79 (0.76, 0.80)		0.77 (0.74, 0.81)	0.79 (0.78, 0.82)	Not Significant 1.00	Not Significant 0.62	N/A	N/A
(mg/min)	98.5 (90.2, 111.9)	90.2 (80.2, 98.5)		75.2 (61.8, 103.5)	70.1 (62.6, 81.8)	Not Significant 0.18	Not Significant 0.11	N/A	N/A
(%)	72.5 (62.6, 76.2)	66.7 (63.1, 76.8)		75.3 (59.2, 85.5)	68.8 (58.8, 80.0)	Not Significant 0.97	Not Significant 0.90	N/A	N/A
Absolute Workload (25 w)	(n=9)	(n=9)							
VO ₂ (ml/min)	1064.6 (918.5, 1234.4)	902.3 (779.3, 944.1)		758.7 (724.5, 843.8)	700.8 (660.4, 716.1)	0.03	0.0009	Not Significant 0.09	0.0006
EE (kcal/min)	5.0 (4.4, 5.9)	4.3 (3.7, 4.6)		3.6 (3.6, 4.0)	3.3 (3.2, 3.5)	0.03	0.002	Not Significant 0.24	0.002
EE (kcal/min/kgFFM)	0.08 (0.07, 0.10)	0.07 (0.06, 0.09)		0.08 (0.07, 0.09)	0.08 (0.07, 0.09)	Not Significant 0.07	Not Significant 0.28	N/A	N/A
Fatty Acid Oxidation (RER)	0.83 (0.80, 0.84)	0.82 (0.79, 0.85)		0.84 (0.82, 0.86)	0.84 (0.78, 0.85)	Not Significant 0.50	Not Significant 0.45	N/A	N/A
(mg/min)	331.5 (264.3, 363.1)	261.5 (238.3, 296.6)		205.4 (177.9, 277.6)	183.4 (177.7, 251.4)	Not Significant 0.05	Not Significant 0.08	N/A	N/A
(%)	52.6 (48.0, 62.3)	54.9 (47.3, 66.5)		49.1 (44.2, 56.8)	51.1 (47.3, 71.2)	Not Significant 0.50	Not Significant 0.45	N/A	N/A
Gross Efficiency (%)	7.2 (6.1, 8.1)	8.3 (7.9, 9.8)		9.9 (9.1, 10.0)	10.9 (10.2, 11.3)	0.02	0.002	Not Significant 0.24	0.002
Net Efficiency (%)	10.0 (7.7, 11.0)	11.5 (10.3, 13.7)		13.5 (11.4, 13.9)	14.6 (13.9, 14.9)	0.03	0.005	Not Significant 0.40	0.002

	Adults with Severe Obesity			Control Groups		P-values		Adjusted P-values ^c	
	Baseline	Post-intervention	Class 1 Obese	Normal Weight	Across Groups ^b	Baseline vs. Post-intervention ^a	Class 1 Obese	Post-intervention vs. Class 1 Obese	Post-intervention vs. Normal Weight
Relative Workload (60% VO _{2peak})	(n=11)	(n=11)							
VO ₂ (ml/min)	1242.8 (1152.7, 1320.6)	1029.7 (969.7, 1140.2)	1369.8 (1334.0, 1502.0)	1275.5 (1102.1, 1623.3)	0.03	0.005	0.024	Not Significant 0.07	
EE (kcal/min)	6.0 (5.4, 6.4)	5.0 (4.5, 5.4)	6.9 (6.7, 7.4)	6.5 (5.4, 8.4)	0.02	0.005	0.019	Not Significant 0.06	
EE (kcal/min/kg FFM)	0.10 (0.09, 0.11)	0.09 (0.08, 0.10)	0.17 (0.14, 0.17)	0.17 (0.15, 0.18)	0.0001	0.04	0.0006	0.0004	
Fatty Acid Oxidation (RER)	0.84 (0.80, 0.88)	0.83 (0.80, 0.85)	0.92 (0.89, 0.99)	0.90 (0.84, 0.96)	0.02	Not Significant 0.97	Not Significant 0.030	0.015	
(mg/min)	382.4 (256.6, 432.3)	286.1 (248.8, 320.6)	191.8 (16.1, 285.3)	207.4 (94.4, 264.5)	Not Significant 0.13	Not Significant 0.10	N/A	N/A	
(%)	50.9 (35.4, 63.8)	53.4 (45.1, 62.8)	24.7 (2.1, 34.2)	29.6 (12.8, 50.1)	0.02	Not Significant 0.90	Not Significant 0.030	0.023	
Gross Efficiency (%)	10.5 (7.8, 13.1)	12.6 (7.3, 14.5)	15.3 (15.0, 16.8)	16.2 (15.5, 17.2)	0.001	0.02	0.003	0.002	
Net Efficiency (%)	13.2 (10.6, 16.2)	16.0 (9.2, 18.1)	18.8 (17.3, 20.1)	19.5 (18.3, 20.0)	0.005	0.007	0.019	0.004	

^aDifferences between baseline and post-intervention assessed with the Wilcoxon signed-rank test

^bKruskal-Wallis one-way analysis of variance compared post-intervention adults with severe obesity and control groups

^cSignificance set at p 0.025 using Bonferroni adjustment for post hoc, nonparametric comparisons for multiple groups