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Influence of adiposity on the thermic effect of food and exercise in lean and obese adolescents

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Summary

To determine the effect of adiposity on adolescent energy expenditure compartments, basal energy expenditure (BEE) together with the thermic effect of food at rest and during post-exercise recovery were compared in eight lean (BMI < 25 kg/m^2) and eight obese (BMI > 27 kg/m^2) 15-year-old adolescent males at the same stage of pubertal development. Both groups were of equivalent fat-free mass.

Continuous energy expenditure was measured by open circuit indirect calorimetry for periods of up to three hours following: (i) an overnight fast; (ii) a test meal; and (iii) moderate exercise after a further serving of the test meal. Repeat baseline measurements were taken on the following day.

Absolute basal energy expenditure was higher in obese than in lean subjects. No significant differences were observed between groups in relation to BEE per kg total fat free-mass. Thermogenesis was significantly greater in the lean relative to the obese group under resting conditions (61.1 ± 8.9 *vs.* 41.4 ± 5.1 kcal/3 h; $P < 0.05$) and in the post-exercise period (69.4 ± 6.3 *vs.* 49.0 ± 5.6 kcal/3 h; $P < 0.05$). Of the body composition parameters, percentage fat mass was the best predictor of the thermic effect of food at rest ($R = -0.53$; $P = 0.03$) and post-exercise recovery ($R = -0.61$; $P = 0.012$).

The results indicated that: (i) even when lean and obese adolescents are comparable with respect to fat-free mass, thermogenesis is blunted in obese subjects; and (ii) the best body composition predictor of thermogenesis in adolescents is percentage fat mass.

Keywords: thermogenesis, indirect calorimetry, obesity, adolescents

Introduction

Obesity in adults and adolescents is associated with increased absolute energy expenditure.[1] A higher basal energy expenditure (BEE) in obesity is related to a larger lean body mass as well as to greater percentage body fat.[2–4]

Decreased meal-induced thermogenesis has been suggested as a contributory factor in obesity. Quantitatively, however, since the thermic effect of food is a rather minor component of total energy expenditure, a defect in it would be associated with only minimal differences in energy expenditure in obese *vs.* lean subjects.

Further, discrepancies exist in published data in relation to the acute effect of physical activity on postprandial energy expenditure (PEE). Some authors suggest that exercise enhances postprandial thermogenesis in lean but not obese subjects[5,6] while others fail to confirm this effect.[7,8] The acute interactions between exercise and food ingestion have been investigated by Segal *et al.*[5,9,10] in lean and obese adults. Their evidence supports an interaction between an acute bout of exercise and food ingestion, in which the first enhances the thermic effect of the latter. These authors have also shown that this thermogenic enhancement is diminished in the obese patient.

Although it may be generally accepted that the principal determinant of basal energy expenditure is lean body mass, differences of opinion exist as to the factors predicting postprandial and/or postprandial/post-exercise thermogenesis, probably because of the difficulties in distinguishing the contributions of lean body mass, fat mass or body mass index since these factors are strongly inter-related.

Total and basal energy expenditure are well documented in lean and obese adolescents[1,2,11] but a relative paucity of information exists regarding the other components of energy expenditure in humans particularly during the growth phase. An important part of adolescent energy is expended in tissue synthesis and growth; the latter being the principal factor that distinguishes between adult and adolescent metabolism. In addition, it is not known whether the obese adolescent already has a blunted thermogenesis which may be maintained into adulthood and, furthermore,

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the factors that might explain this defect are consistently ignored.

Hence, the objectives of this study were to compare BEE, postprandial and postprandial/post-exercise energy expenditure between lean and obese adolescents and, subsequently, by comparing the response of groups of adolescents with similar FFM but different body fat content, to clarify the relationship between body composition and thermogenesis.

Subjects and methods

Subjects

Eight obese 15-year-old male adolescents and their lean counterparts were selected for investigation from among subjects of a previous study.[12] The obese subjects had a BMI > 27 kg/m^2 while the lean subjects had a BMI < 25 kg/m^2. All were at stage 3 of puberty as described by Tanner.[13] All subjects were healthy with no personal or family history of diabetes mellitus or other metabolic diseases. An oral glucose tolerance test was administered, according to the criteria of the National Diabetes Data Group,[14] to ensure that all obese patients had normal glucose tolerance. Highly aerobically-trained individuals were not accepted into the study in order to eliminate variations in metabolic response resulting from differences in levels of cardiorespiratory fitness. The adolescents were non-smokers and were not taking any medications. Fully-informed written consent for participation was obtained from the parents and the study was approved by the hospital's ethical committee.

Study protocol

Figure 1 shows the study design. One week before the test, each subject's sub-maximal aerobic fitness was assessed. No strenuous exercise was allowed during the 24 h period before the test. For each subject, the evening meal of the day prior to the study consisted of 600 kcal in the form of a liquid formula (Pentadrink®, Nutrition Laboratories, Zoetermeer, The Netherlands) supplemented with 10 g/100 ml of a protein solution (Proteínas Concentradas®, Clinical Nutrition, Mataró, Spain).

As part the clinical work-up for the study, the BEE was determined for each individual by indirect calorimetry conducted over a 30 min period using Weir's formula.[15]

On the day of the test, each individual was given a meal representing 1.3 times the energy relative to the previously determined BEE. This excess to requirements was used to ensure maintenance of body weight during the test period.[16] The energy requirement was calculated and administered in three isocaloric amounts; two of which were administered in the metabolic laboratory during the day and the third on the same night at home. The energy contents of the test meal were 795 ± 113 kcal and 876 ± 127 kcal (30% protein, 32% fat, 38% carbohydrate) in lean and obese groups respectively.

Energy expenditure was continuously measured for 3 h in the postprandial and the postprandial/post-exercise periods.

Aerobic fitness test

Submaximal aerobic fitness was determined by a continuous, multi-stage exercise test on a cycle ergometer (ERG 550 Bosch, Berlin, Germany). Prior to the submaximal test, time was allotted for the subjects to familiarize themselves with cycling on the ergometer at a constant pedalling rate while breathing through the apparatus used for metabolic measurements. The subjects began pedalling at 50 rev/min with zero external resistance. The work-rate was increased in 25 W stages every 2 min until heart rate was ⩾ 170 beats/min (defined as physical working capacity, PWC170).[17] This test measures the work required by a subject when his cardiac frequency reaches 170 beats/min. This system is considered better than VO_2max for measuring the aerobic resistance capacity in adolescents.[18,19] A linear relationship exists between physical effort and cardiac frequency at the 100–170 beats/min level. A relationship between pulse and oxygen consumption during physical activity has also been reported.[20] Hence, cardiac frequency is a useful parameter for predicting oxygen consumption. From the results of the multi-stage exercise test and by regression analysis, the intensity of physical activity required to reach a cardiac frequency of

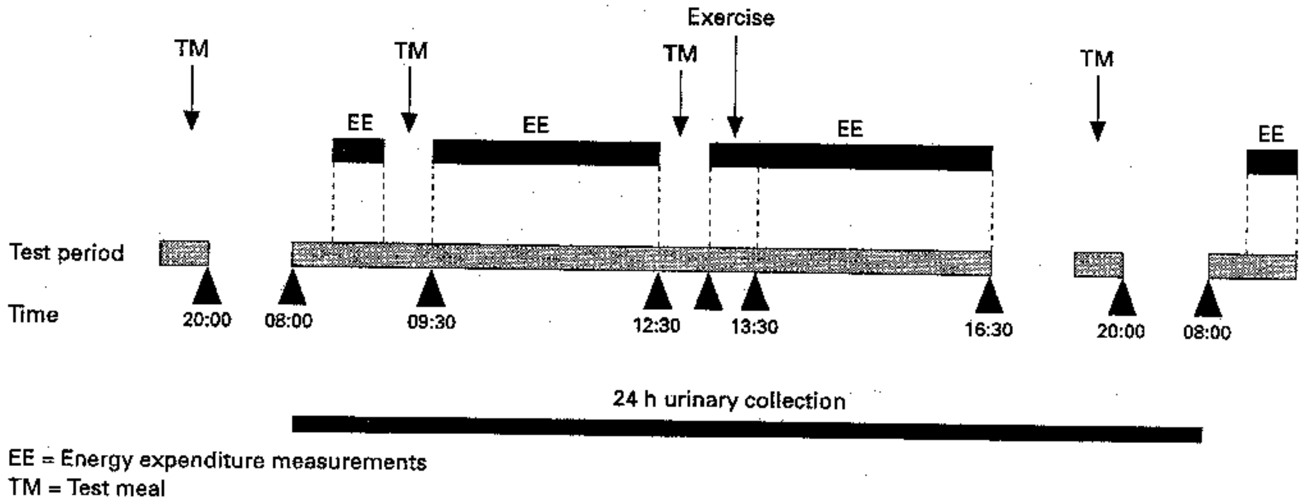

Figure 1 Experimental design.

170 beats/min (PWC170) was calculated. The exercise intensity was adjusted according to each subject's level of aerobic fitness, and the level of physical exercise on the day of the test for a period of 30 min on the ergometer was maintained at 70% of the PWC170.

Energy expenditure measurements

EE was measured by open circuit indirect calorimetry (SensorMedics Energy Expenditure Unit 2900; SensorMedics, Bilthoven, The Netherlands). The equipment includes a mass flowmeter transducer, a Beckman zirconium O_2 analyser and a Beckman LB-2 non-dispersive infra-red CO_2 analyser. The subjects breathed through a Hans–Rudolph non-rebreathing valve and used a face mask during the exercise period. During the postprandial and post-exercise period, exhaled air was collected using a hood. This system allows the continuous measurement of oxygen consumption (VO_2), the production of carbon dioxide (VCO_2) and the respiratory quotient ($RQ = VCO_2/VO_2$). Before and after each test, O_2 and CO_2 sensors were calibrated using different gas mixtures of known N_2, O_2 and CO_2 concentrations. Periodically, the precision of the measurement was confirmed.[21] To calculate the energy expenditure, the following formula of Bursztein[22] was used:

$$\text{EE (kcal)} = 3.581\ VO_2\ \text{(litres)} + 1.448\ VCO_2\ \text{(litres)} - 1.773\ \text{urinary nitrogen (g/24 h)}$$

The urinary nitrogen was determined by the Kjeldahl method[23] on the urine collected during the 24 hours of the test day.

On the night prior to the test, the subjects consumed the assigned 600 kcal liquid formula diet (Figure 1). At 08:00 h the following morning, the VO_2 and VCO_2 at basal conditions were measured every minute for 30 min by indirect calorimetry and from this the BEE (day 1) was calculated. Following this, the first part of the test meal was consumed within 30 min and the VO_2 and VCO_2 were measured over the subsequent 3 h. The PEE was calculated from the area under the curves of the EE measurements and expressed in kcal/min. Postprandial thermogenesis (PT) was calculated as [postprandial EE area (kcal/3 h) − [BEE (kcal/min) × 180 min] and expressed as kcal/3 h or as a function of the energy contained in the test meal. The second part of the test meal was then consumed over a 30 min period and the VO_2 and VCO_2 were measured over a 30 min exercise period and for the following 3 h of recuperation. From these data, the postprandial/post-exercise energy expenditure was calculated and expressed as kcal/min. Postprandial/post-exercise thermogenesis (PPT) was calculated from [postprandial/post-exercise EE area (kcal/3 h)] − [BEE (kcal/min) × 180 min] and expressed as kcal/3 h or as a function of the energy contained in the test meal.

At 20:00 h, the subjects consumed the third part of the diet at home. At 08:00 h the following morning, the VO_2 and VCO_2 at basal conditions were repeated, from which day 2 BEE was calculated.

All the thermogenesis measurements were performed on the same day so as to minimize the effects of the 4–7% day-to-day variability in basal energy expenditure[24] on the measured parameters.

Anthropometric measurements

Skinfold measurements were made at the triceps, biceps, supra-iliac and subscapular regions. Chest size, height and weight were measured using the Holtain apparatus. The measurements were made by a single investigator according to a standardized protocol. Body fat mass was estimated using the following equation of Garcia-Llop *et al.*:[25]

$$\text{body fat mass} = -27.98 + [25.30 \times \log \Sigma\ 4\text{SF(mm)}] + [0.2345 \times \text{BMI}]$$

where BMI (body mass index) = body weight/height^2 (kg/m^2) and Σ 4SF is the sum of the four skinfold measurements. The fat-free mass (FFM) was calculated by subtraction of the estimated fat mass from the total body weight.

Analysis of data

Statistical analyses were conducted using the SPSS/PC package (SPSS Inc, Chicago, Illinois, USA). For the comparison of means, Student's paired and unpaired *t* tests were used. All values at the 0.05% level were considered significant.

Results

The subjects' characteristics are presented in Table 1. There were no significant differences in age, height and FFM between lean and obese adolescents. The two groups differed with regard to skinfold measurements, weight, BMI and body fat content. PWC170 was not significantly different between the two groups when expressed in absolute form, but, relative to total body weight, PWC170 was significantly lower for the obese than the lean adolescents ($P < 0.001$).

Pre-exercise period

The mean day 1 BEE was not significantly different between the two groups when expressed either as kcal/min or as kcal/kg FFM/h (1.64 ± 0.06 kcal/kg FFM/h and 1.71 ±

Table 1 Subjects' characteristics

	Lean *(n = 8)*	*Obese* *(n = 8)*
Body weight (kg)	59.2 ± 8.3	74.3 ± 9.5**
Height (cm)	166 ± 8	160 ± 7
Body mass index (kg/m^2)	21.5 ± 2.9	29.1 ± 2.5**
Mid-arm circumference (cm)	25.6 ± 1.8	32.6 ± 2.9**
Triceps skinfold (mm)	17.3 ± 9.5	30.2 ± 6.7*
Body fat (kg)	12.7 ± 5.9	24.9 ± 2.9**
Body fat (%)	20.7 ± 7.4	33.5 ± 2.4**
Body fat-free mass (kg)	46.6 ± 4.7	49.4 ± 6.4
PWC170 (W)	115.7 ± 13.8	109.1 ± 18.6
PWC170/kg body weight	1.97 ± 0.20	1.48 ± 0.24**

All values are expressed as means ± s.d.
* $P < 0.01$; ** $P \leq 0.001$ *(Student's t test).*
All subjects were at stage 3 of puberty as described by Tanner.[13]

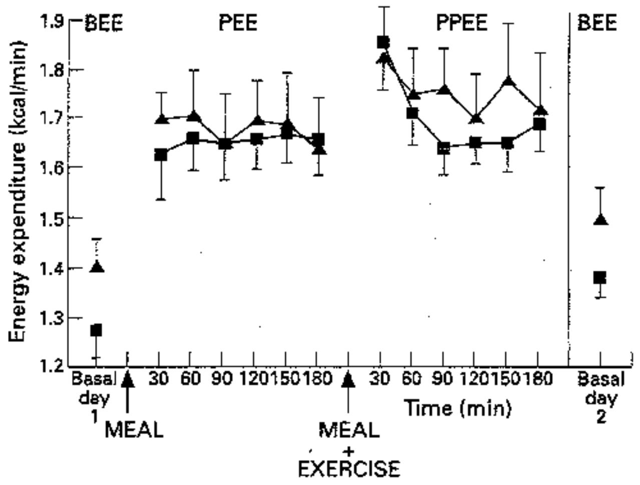

Figure 2 Energy expenditure throughout the study period in relation to groups studied. All postprandial (PEE) and postprandial/post-exercise (PPEE) measurements were significantly different ($P <$ 0.01) from BEE (basal energy expenditure). day 1 BEE *vs.* day 2 BEE ($P < 0.05$) in obese (▲) and lean (■) groups.

Table 2 Comparisons of energy expenditure parameters between lean and obese adolescents

	Lean *(n = 8)*	*Obese* *(n = 8)*
Day 1 BEE (kcal/min)	1.27 ± 0.06	1.40 ± 0.07
PT		
kcal/3 h	61.1 ± 8.9	41.4 ± 5.1*
% energy intake	7.87 ± 1.20	4.80 ± 0.64*
PEE (kcal/min)	1.61 ± 0.07	1.63 ± 0.08
PPT		
kcal/3 h	69.4 ± 6.3	49.0 ± 5.6*
% energy intake	8.96 ± 1.00	5.78 ± 0.76*
PPEE (kcal/min)	1.66 ± 0.06	1.68 ± 0.06
Day 2 BEE (kcal/min)	1.38 ± 0.06†	1.49 ± 0.07‡

All values are expressed as means ± s.e.m.
** P < 0.05, lean vs. obese (Student's t test for unpaired data).*
† P < 0.01; ‡ P < 0.05, day 1 BEE vs. day 2 BEE (Student's t test for paired data).
BEE = basal energy expenditure; PT = postprandial thermogenesis; PEE = postprandial energy expenditure; PPT = postprandial/post-exercise thermogenesis; PPEE = postprandial/post-exercise energy expenditure.

0.06 kcal/kg FFM/h in lean and obese groups respectively). Stepwise multiple regression analysis shows that FFM is the primary predictive factor of day 1 BEE ($R = 0.68$; $P <$ 0.005). In all individuals, a statistically significant increase in PEE relative to basal values was observed (Figure 2). In both groups, PEE at 180 min was significantly higher than basal values.

PEE, expressed as a percentage increase relative to basal values, was consistently higher in lean subjects compared to obese subjects.

Postprandial thermogenesis (PT), expressed as kcal/3 h or as a percentage of energy intake, was significantly higher in the lean than in the obese group (Table 2).

Post-exercise period

Postprandial/post-exercise energy expenditure (PPEE), expressed in kcal/min or in kcal/kg FFM/min, was not significantly different between groups. PPT, expressed as kcal/3 h or as a percentage of energy intake, was significantly higher in lean than obese adolescents (Table 2).

No significant differences were found for PEE compared to PPEE nor PPT compared to PT for the two groups.

The lean and obese day 2 BEE were significantly higher than the corresponding value on day 1.

Stepwise multiple regression indicated that percentage fat was the best predictor (among body composition parameters, which included percentage fat, FFM, body weight and BMI) of the thermic effect of food in the postprandial ($R = -0.53$; $P = 0.03$) and postprandial/post-exercise ($R = -0.61$; $P < 0.012$) states. The correlations between aerobic fitness (PWC170) and the thermic effect of food, at rest or in the post-exercise period, were not statistically significant.

Discussion

The two groups investigated in the present study were homogeneous with respect to age, pubertal stage and fat-free mass. Body fat content was the greatest difference between lean and obese adolescents studied. In terms of BEE/kg body weight or BEE/kg FFM, the adolescents in this study were similar to those described by Dietz *et al.*[2] Similarly, the mean BEE predicted by equations of the WHO/FAO[16] were 1.18 kcal/min and 1.35 kcal/min for lean and obese subjects compared to our findings of 1.27 kcal/min and 1.40 kcal/min respectively.

Our study showed that absolute BEE was higher in the obese subjects, but similar to that in lean subjects if expressed in terms of total body weight or of FFM. These findings support the hypothesis that BEE is principally determined by FFM rather than fat mass. Indeed, stepwise multiple regression analysis shows that FFM is the primary predictive factor of the day 1 BEE ($R = 0.68$; $P < 0.005$).

Pre-exercise period

In measuring thermogenesis, the administered energy represented 1.3 times the individual BEE in order to ensure that energy intake for body weight maintenance was equivalent between individuals. The relative proportion of protein-derived calories was 30%, since Belko *et al.*[26] demonstrated that maximum PT was achieved in adults with a test meal containing 30–45% of calories derived from protein.

In each individual, we observed a significant increase in EE at 30 minutes postprandially. Postprandial thermogenesis remained elevated over the three hours of the test period. These results are similar to those obtained by Segal *et al.*[27] and indicate that PT could extend well beyond three hours. We were unable to validate the time course of this elevation, since a more protracted protocol, of six hours or more, was not acceptable to the parents of our lean subjects.

Postprandial energy expenditure expressed as kcal/min or as kcal/kg FFM was similar between lean and obese patients and could be explained by the differences in BEE in the two groups.

The present study indicated that obesity was associated with a diminished capacity for thermogenesis but not with reduced resting energy expenditure. Previous studies[28,29] have suggested that blunted thermogenesis is related to insulin resistance and impaired glucose tolerance; a frequent complication of obesity. All our subjects had normal glucose tolerance but the obese adolescents were hyperinsulinemic compared with the lean (fasting insulin: $20 \pm 9\,\mu$U/ml, $n = 5$, in obese subjects *vs.* $11 \pm 2\,\mu$U/ml, $n = 8$, in lean subjects; $P = 0.058$, not significant) and it is possible that our obese subjects have a degree of insulin resistance as described elsewhere.[30] Other possible mechanisms for the reduced thermic effect of food in obese subjects include reduced sensitivity to the actions of thermogenic hormones (catecholamines and thyroid hormones) stimulated by the ingestion of a meal with or without exercise, or a reduced thermogenic capacity of brown adipose tissue. We were unable to investigate these aspects in the present study.

Postprandial/post-exercise period

In the period following exercise, thermogenesis was diminished in obese subjects compared to lean. Since the effect of exercise on postprandial thermogenesis depends on the degree of physical training,[31] the exercise intensity had been adjusted according to each individual's level of aerobic fitness to preclude any significant contribution of cardiorespiratory fitness. Also, no subjects had participated in any systematic physical training programme.

Several conflicting assessments of the effect of exercise on PT in obese and non-obese subjects under various experimental conditions have been reported.[5,9,21,26,27,32–34] While a number of investigators have demonstrated that exercise facilitated PT in lean[5,27,33,35,36] and obese subjects,[37] other investigators[7,8,32] were unable to confirm the findings. Segal *et al.*[5] showed that, compared to the postprandial thermogenesis at rest, there was a significant increase in the thermic effect of food in obese adult patients when the meal followed an exercise period. The authors suggested that this could be explained by the increased glucose uptake and glycogen synthesis in muscle, secondary to an increased sensitivity to insulin induced by acute exercise. In our study, however, although there were increases in PPT relative to PT (Figure 2 and Table 2), this increase was not significant in either lean or obese subjects. The design of our study precludes an assessment of how much of the increased thermic response is due to the exercise alone, the second meal alone or the interaction between the two factors. Measurements of post-exercise EE in the fasting state performed at the same time of day would be necessary to resolve this question. However, it is of considerable interest that the response of obese and lean subjects is significantly different as regards PT as well as PPT.

Of further interest was the observation of a consistent increase of BEE on day 2 relative to day 1, indicating a prolonged effect of a combination of a meal and exercise on postprandial/post-exercise energy expenditure. The influence of a hyperproteic diet with exercise on PPT represents a small effect on the total energy balance, whereas its influence on BEE is more important since the latter represents a larger percentage of total EE and, as such, has a greater influence on effective energy utilization.

Of all the body composition and other variables studied, the best predictor of the postprandial thermogenesis and of postprandial/post-exercise thermogenesis was the fat mass. This supports the concept that body fatness, rather than fat-free mass, is the major determinant of the thermic response to a meal.

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