

Assessment of energy expenditure associated with physical activities in free-living obese and nonobese adolescents^{1–3}

Stefano Lazzar, Yves Boirie, Abdelali Bitar, Christophe Montaurier, Jean Vernet, Martine Meyer, and Michel Vermorel

ABSTRACT

Background: Information on activity patterns and the energy cost of activities is critically missing.

Objective: We measured the energy cost of and time devoted to various activities in obese and nonobese adolescents.

Design: Daily energy expenditure (DEE) and its main components were determined in 27 obese and 50 nonobese adolescents aged 12–16 y by using whole-body calorimetry with the same activity program and the heart rate–recording method in free-living conditions.

Results: In whole-body calorimetry, energy expenditures (EEs) during sleep and sedentary activities were 18.9% and 21.5%, respectively, higher in obese subjects than in nonobese subjects ($P < 0.001$), but not significantly different after adjustment for fat-free mass (FFM). EEs during walking and DEEs were significantly higher in obese than in nonobese subjects, both absolutely (71% and 33%, respectively) and after adjustment for body weight or FFM (16% and 11%, respectively). In free-living conditions, EEs associated with physical activities did not differ significantly between obese and nonobese subjects, but they were 51% lower in obese subjects after adjustment for body weight ($P < 0.001$). The obese adolescents spent more time in light physical activities but much less time in moderate activities and sports than did the nonobese subjects. The activity-related time equivalent corrected for sedentary EE (ARTE EE₂) averaged 69 and 122 min/d in obese and nonobese subjects, respectively ($P < 0.01$).

Conclusion: Physical activity is low in obese subjects and can be assessed satisfactorily in both obese and nonobese adolescents by using ARTE EE₂ when DEE and the basal metabolic rate are known. *Am J Clin Nutr* 2003;78:471–9.

KEY WORDS Energy expenditure, whole-body calorimetry, free-living conditions, adolescents, obesity, body composition, physical activity

INTRODUCTION

The prevalence of obesity in children has increased dramatically during the past few decades in the United States, Australia, and Europe (1–5). Obesity arises from a mismatch between energy intake and energy expenditure (EE) that results in a net accumulation of energy stores, mainly as fat, in the body. A low level of physical activity is a major risk factor for excess fat gain in children (6–8).

Because of their higher body weight (BW) and greater fat-free mass (FFM), obese children and adolescents have higher basal metabolic rate (BMR), sleeping metabolic rate (sleeping MR), daily EE (DEE), and physical activity EE than do nonobese subjects

(9–11). However, obese children generally spend less time in physical activities and more time in sedentary activities than do their age-matched counterparts (6, 10, 12, 13), which suggests that both EE associated with physical activity and EE associated with sedentary activities (sedentary EE) must be measured accurately. Most studies have used the doubly labeled water method for the measurement of the mean DEE of subjects in free-living conditions over a period of 10–15 d (9, 14). However, this method does not give any information about activity patterns and EE associated with physical activities. More detailed information about EE associated with physical activities in free-living conditions has been obtained by using the heart rate (HR)–recording method and accelerometry (15, 16).

Several authors estimated EE associated with physical activities [activity EE (AEE)] as $DEE - (BMR \times 1440)$ (9–17) or as $DEE - [(BMR \times 1440) + TEF]$, where TEF is the thermic effect of food. Activity-related EE has also been derived from AEE by using the activity-related time equivalent [ARTE EE = $AEE / (\text{reference physical activity MR} - \text{sleeping or resting MR})$] (18). As Schutz et al (19) said, “The ARTE EE index is a practical measurement of physical activity because it is adjusted for each subject’s exercise economy and enables comparisons of subjects with different body weights and different exercise energy economics.” However, AEE and ARTE EE include the increase in EE above sleeping MR or BMR during sedentary activities. Therefore, the seeming paradox that obese children have higher AEEs than do nonobese children could be explained by 1) the greater FFM and fat mass (FM) of the obese children, 2) their higher energy costs for walking and running (20), or 3) the miscalculation of AEE and ARTE EE. These latter points are particularly relevant because the differences

¹ From the Energy and Protein Metabolism Research Unit, Institut National de la Recherche Agronomique (INRA), University of Auvergne, Centre de Recherches en Nutrition Humaine, Clermont-Ferrand, France (SL, YB, and CM); the Department of Biology, Applied Physiology Laboratory, Faculty of Sciences, El Jadida, Morocco (AB); the Energy and Lipid Metabolism Research Unit, INRA Theix, St Genès Champanelle, France (JV and MV); and the Hôtel-Dieu Pediatric Hospital, Clermont-Ferrand, France (MM).

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³ Address reprint requests to M Vermorel, Energy and Lipid Metabolism Research Unit, INRA Theix, 63122 Saint-Genès Champanelle, France. E-mail: vermorel@clermont.inra.fr.

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between sedentary MR and sleeping MR or BMR are greater in obese subjects than in nonobese subjects in proportion to the higher FFM of the obese subjects. Consequently, AEE and ARTE EE should be corrected for the contribution of sedentary activities. Therefore, information about activity patterns and the energy cost of activities that is needed for evaluating the contribution of physical activity to BW control in obese children and adolescents is missing.

The objectives of the present study were to measure DEE and its main components, to measure the time devoted to and the energy cost of various sedentary and physical activities in obese and nonobese adolescents in standardized and in free-living conditions, and to determine the appropriate methods of assessing EE associated with physical activities in obese children and adolescents.

SUBJECTS AND METHODS

Severely obese ($n = 13$ boys, 14 girls) and nonobese ($n = 23$ boys, 27 girls) adolescents aged 12–16 y participated in this study. Before the study began, the purpose and objectives were carefully explained to each subject and his or her parents. Written informed consent was obtained from all adolescents and their parents. The experimental protocol was approved by the University Ethical Committee on Human Research for Medical Sciences.

All subjects were healthy and not receiving any medication known to influence energy metabolism. All obese subjects had a body mass index (in kg/m^2) above the 97th percentile for chronological age (21), whereas the body mass index in all nonobese subjects was below the 75th percentile. The obese and nonobese subjects followed similar experimental protocols, but the obese subjects spent 5 d/wk in a specialized institution and the weekend at home, whereas the nonobese subjects lived at home. All of the subjects went to the same schools 5 d/wk. The nonobese subjects represented 80% of a population who participated in a previously reported study (22, 23).

Physical characteristics and body composition

BW was measured to the nearest 0.1 kg with the use of a calibrated manual-weighing scale (Seca 709; Seca, Hamburg, Germany). Height was measured to the nearest 0.5 cm with the use of a standardized wall-mounted height board. FM, FFM, and percentage body fat of nonobese subjects were assessed with the use of both the skinfold-thickness method (24) and bioimpedance analysis (model BIA 101; RJL System, Detroit) with 4 cutaneous probes and current at 50 kHz. Hologic QDR-4500 dual-energy X-ray absorptiometry equipment and TOTAL-BODY SCAN software, version 9.10 (Hologic Inc, Bedford, MA), were used for obese subjects because this is considered the most reliable and accurate method for use in such persons (25–27).

Measurement of energy expenditure

BMR was determined between 0800 and 0930 after an overnight fast by means of open-circuit, indirect computerized calorimetry (Deltatrac calorimeter; Instrumentarium Oy, Datex Division, Helsinki) with a rigid, transparent, ventilated canopy. After the subjects, who were supine, reached a steady state, the BMR was measured for 45 min. Oxygen consumption and carbon dioxide production, standardized for temperature, barometric pressure, and humidity, were measured at 1-min intervals, and the values were averaged over the entire measurement period. EE was derived from the measured oxygen uptake and carbon dioxide output according

to the formula of Lusk (28). Before each test, the gas analyzers were calibrated with a reference gas mixture (95% O_2 and 5% CO_2).

In standardized conditions, EE was measured continuously with the use of 2 comfortable, open-circuit, whole-body calorimeters (29). Gas exchanges were computed from outlet air flow, differences in gas concentrations between air entering and leaving the calorimeter, atmospheric pressure, chamber air temperature, and hygrometry after correction for the drift and time of response of the gas analyzers and the variations of the volumes of carbon dioxide and oxygen in the calorimeters. In addition, the validity of gas exchange measurements was checked gravimetrically (30). EE was calculated from the minute-to-minute measurement of gas exchanges and mean urinary nitrogen excretion by using the equation of Brouwer (31). HR was measured by telemetry (Life scope 6; Nikon Kohden, Tokyo) and recorded continuously during each subject's stay in the calorimeters.

Each subject spent 36 h in the calorimeters, one evening and one night for adaptation and 24 h for measurements. During this period, the subjects followed a standardized activity program composed of 4 main periods: 1) sleeping (8.5 h), 2) sedentary activities [watching television, playing video games or board games, listening to music, doing homework (10.5 h), and eating meals (2 h)], 3) miscellaneous activities [washing and dressing, making the bed, and tidying the room (1 h)], 4) six 20-min exercise sessions of walking on a treadmill at 3 different speeds (4, 5, and 6 km/h; 2 h) with a break of 70 or 100 (at lunch) min between the sessions. The obese subjects selected their own speed of comfortable walking on the treadmill before the beginning of measurements in the calorimeters. Then, for each walking session, speed and slope were adjusted to achieve the stated 3 horizontal speeds (32).

Subjects were offered copious meals. The quantities of each food offered and not eaten were determined by using a balance accurate to within 0.1 g. The nutrients and energy intakes were assessed with the use of MICRO 6 software [version 4.0; Gestion d'Enquêtes Nutritionnelles Informatisées (GENI), Villers les Nancy, France] according to the nutritive value of foods (33). The TEF was estimated to be 25% lower in obese subjects than in nonobese subjects, according to the results obtained in prepubertal children over 3-h periods (34), and it was set at mean values of 10.0% and 7.5% of energy intake for the nonobese and obese adolescents, respectively.

For each subject, the relation between data for EE and for HR recorded in the room calorimeters over a 24-h period was computed (35). In addition, individual specific relations were computed between EE and HR data during sleep and seated activities to reduce the prediction error of the EEs for these activities.

In free-living conditions, the levels of physical activity and EE were assessed by using the HR-recording method and an activity diary. HR was monitored for 7 consecutive days with the use of HR monitors (Polar Electro KY, Kempele, Finland). The volunteers were given a detailed explanation of the activity diary form and method. They were instructed to record regularly and carefully all of their activities (type, intensity, times of beginning and end of each activity) every day during the 7-d recording period. They were also equipped with a tri-axial accelerometer (Tri-Trac-R3D; Research Ergometer, Hemokinetics Inc, Madison, WI) to ensure that the increases in HR resulted from physical activity and not from interferences. However, the accelerometers could not be calibrated so that each subject could adequately assess physical activity EE from the accelerometric data. We visited the subjects every evening to check and complete the activity diary in order to control the HR monitor and the tri-axial accelerometer. We then

TABLE 1
Physical characteristics and body composition of obese and nonobese adolescents[†]

	Boys		Girls		P		
	Nonobese (n = 23)	Obese (n = 13)	Nonobese (n = 27)	Obese (n = 14)	Obesity	Sex	Obesity × sex interaction
Age (y)	14.2 ± 0.31	13.5 ± 0.31	13.8 ± 0.31	14.7 ± 0.31	0.754	0.171	0.007
Body weight (kg)	51.8 ± 2.62	89.9 ± 2.62	47.5 ± 2.62	94.2 ± 2.62	0.001	1.000	0.073
Height (cm)	164.0 ± 2.21	163.1 ± 2.21	160.1 ± 2.21	164.5 ± 2.21	0.392	0.536	0.197
BMI (kg/m ²)	19.1 ± 0.61	33.5 ± 0.61	18.5 ± 0.61	34.7 ± 0.61	0.001	0.601	0.116
Fat-free mass (kg)	42.8 ± 1.78	52.7 ± 1.78	37.0 ± 1.78	52.1 ± 1.78	0.001	0.053	0.109
Fat mass (%)	17.6 ± 0.84	41.6 ± 0.84	21.8 ± 0.84	44.5 ± 0.84	0.001	0.001	0.384

[†]Least-squares $\bar{x} \pm SE$. Significance by ANOVA of the main effects of obesity and sex and for obesity × sex interaction.

compared the activity records with the HR and accelerometer graphics to check the agreement of the 3 recordings.

DEEs of subjects and EEs during physical activities were computed from the HRs recorded during 7 d by using the relation between HR and EE computed for each individual. In addition, the EEs during sleep (sleeping EE) and sedentary activities (sedentary EE) were computed from HR recordings, and the corresponding specific relations were computed for each subject. For clarification, the mean EE during an activity (kJ/min) is called metabolic rate (MR).

Physical activity EE (kJ/d) was calculated in 3 different ways:

$$AEE_1 = DEE \text{ (kJ/d)} - [\text{sleeping MR (kJ/min)} \times 1440 \text{ (min/d)}] \quad (1)$$

$$AEE_2 = DEE \text{ (kJ/d)} - [\text{sleeping MR (kJ/min)} \times 1440 \text{ (min/d)}] + [0.1 \times DEE \text{ (kJ/d)}] \quad (2)$$

$$PAEE \text{ (kJ/d)} = DEE \text{ (kJ/d)} - [\text{sleeping EE (kJ/d)} + \text{sedentary EE (kJ/d)}] \quad (3)$$

in which PAEE is defined as walking EE (kJ/d) + miscellaneous activities EE (kJ/d), and sedentary EE is defined as leisure seated activities EE + meals EE + school and homework EE.

In addition, the ARTE EE [min/d (18, 19)] was calculated in 2 ways. ARTE EE₁ corresponds to the definition of ARTE EE (see Introduction):

$$ARTE \text{ EE}_1 = \{DEE \text{ (kJ/d)} \times 0.9 - [\text{sleeping MR (kJ/min)} \times 1440 \text{ (min/d)}]\} / [\text{reference activity (walking MR (kJ/min)} - \text{sleeping MR (kJ/min)})] \quad (4)$$

ARTE EE₂ was introduced to exclude the increase in EE above sleeping MR during sedentary activities and was calculated as

$$ARTE \text{ EE}_2 = \{DEE \text{ (kJ/d)} - [\text{sleeping MR (kJ/min)} \times \text{sleep duration (min/d)}] - \text{sedentary MR (kJ/min)} \times [1440 - \text{sleep duration (min/d)}]\} / [\text{reference activity (walking MR (kJ/min)} - \text{sedentary MR (kJ/min)})] \quad (5)$$

with DEE (kJ/d), sleeping MR, and sedentary MR (kJ/min) as measured in the calorimeters; reference activity: mean activity MR (kJ/min) during walking at 4, 5, and 6 km/h in the calorimeters.

Statistical analysis

The effects of obesity (obese subjects compared with nonobese subjects) and sex (sex group) were analyzed by analysis of variance with the use of PROC GLM software (version 6.12; SAS Institute Inc, Cary, NC). The dependent variables (y)

were the duration (min), the MR (kJ/min), and the EE (kJ) of the various activities. For both models, the adjusted means were computed and compared by using the “LSMEANS” (least-squares means) and the “adjust = bon” (with Bonferroni correction) options of PROC GLM. The least-squares means ± SEs are reported in the text or in the tables. Stepwise multiple regressions were used to determine the significant predictors of sleeping MR. Differences were considered as significant at $P < 0.05$.

RESULTS

Subject characteristics and physical capacities

Age and height did not differ significantly between the obese and nonobese subjects, but for age, there was a significant interaction of obesity and sex. The obese subjects had 42.4 kg more BW, 12.1 kg more FFM, and 30.3 kg more FM, on average, than did the nonobese subjects ($P < 0.0001$; **Table 1**). However, there were no significant differences in body composition between the boys and the girls, except that the percentage of FM was greater in the girls than in the boys ($P < 0.001$).

Energy expenditure in the whole-body calorimeters

FFM and sex were the main determinants of sleeping MR, and they explained 77.2% and 4.0% of the variance, respectively ($P < 0.0001$), whereas FM was not a significant determinant ($P > 0.50$, data not shown). BMR, sleeping and sedentary MRs (kJ/min), and DEE (kJ/d) for the same activity program were significantly ($P < 0.0001$) higher in the obese subjects than in the nonobese subjects (**Table 2**). After adjustment for FFM, however, BMR, sleeping MR, and sedentary MR did not differ significantly between the obese and nonobese subjects ($P > 0.19$, data not shown), whereas DEE was significantly ($P < 0.001$) higher (12.46 ± 0.153 compared with 11.22 ± 0.153 MJ/d). Energy intake in the calorimeters was significantly higher in the obese subjects than in the nonobese subjects (17.44 ± 0.73 compared with 10.97 ± 0.54 MJ/d, $P < 0.001$), as was the estimated TEF (1.31 ± 0.06 compared with 1.10 ± 0.04 MJ/d, $P < 0.004$). However, the difference in TEF accounted for only 5% of the difference in DEE. Similarly, the difference in energy balance between the obese subjects and the nonobese subjects (3.45 ± 0.56 compared with 0.87 ± 0.42 MJ/d, $P < 0.001$) would account for only 7% of the difference in DEE assuming an 0.90 efficiency of energy utilization for lipid gain (36).

Walking MR was significantly ($P < 0.001$) higher in the obese subjects than in the nonobese subjects, and the difference increased from 11.6 to 17.9 kJ/min with speed (Table 2). After

TABLE 2

Energy expenditure (EE) of adolescents as measured by whole-body indirect calorimetry and assessed by using several physical activity indexes¹

	Boys		Girls		P		
	Nonobese (n = 23)	Obese (n = 13)	Nonobese (n = 27)	Obese (n = 14)	Obesity	Sex	Obesity × sex interaction
BMR (kJ/min)	5.23 ± 0.174	5.99 ± 0.174	4.44 ± 0.174	5.47 ± 0.174	0.001	0.001	0.446
Sleeping MR (kJ/min)	5.02 ± 0.193	5.75 ± 0.193	4.21 ± 0.193	5.22 ± 0.193	0.001	0.001	0.498
Sedentary MR (kJ/min)	8.17 ± 0.290	9.36 ± 0.290	6.94 ± 0.290	8.63 ± 0.290	0.001	0.002	0.417
Miscellaneous activities MR (kJ/min)	8.44 ± 0.353	8.60 ± 0.353	7.41 ± 0.353	9.35 ± 0.353	0.006	0.702	0.019
Walking MR (kJ/min)							
4 km/h	15.14 ± 0.731	26.39 ± 0.731	13.49 ± 0.731	24.48 ± 0.731	0.001	0.023	0.873
5 km/h	17.91 ± 0.933	33.02 ± 0.933	16.24 ± 0.933	30.60 ± 0.933	0.001	0.041	0.702
6 km/h	21.59 ± 1.153	39.65 ± 1.153	18.98 ± 1.153	36.73 ± 1.153	0.001	0.025	0.899
DEE (MJ/d)	11.28 ± 0.286	14.50 ± 0.286	9.65 ± 0.286	13.35 ± 0.286	0.001	0.002	0.583
PAEE (MJ/d) ²	2.69 ± 0.122	4.48 ± 0.122	2.39 ± 0.122	4.23 ± 0.122	0.001	0.037	0.834
AEE ₁ (MJ/d) ³	4.05 ± 0.186	6.21 ± 0.186	3.58 ± 0.186	5.82 ± 0.186	0.001	0.030	0.842
AEE ₂ (MJ/d) ⁴	2.92 ± 0.153	4.76 ± 0.153	2.61 ± 0.153	4.48 ± 0.153	0.001	0.073	0.926
ARTE EE ₁ (min/d) ⁵	223 ± 6.8	176 ± 6.8	219 ± 6.8	177 ± 6.8	0.001	0.754	0.690
ARTE EE ₂ (min/d) ⁶	122 ± 1.0	118 ± 1.0	123 ± 1.0	122 ± 1.0	0.002	0.852	0.556

¹Least squares $\bar{x} \pm SE$. BMR, basal metabolic rate assessed by indirect calorimetry; MR, metabolic rate; DEE, daily EE; PAEE, physical activity EE; AEE, activity EE; ARTE, activity-related time equivalent. Significance by ANOVA of the main effects of obesity and sex and for obesity × sex interaction.

²PAEE (kJ/d) = DEE (kJ/d) - [sleeping EE (kJ/d) + sedentary EE (kJ/d)].

³AEE₁ (kJ/d) = DEE (kJ/d) - [sleeping MR (kJ/min) × 1440 (min/d)].

⁴AEE₂ (kJ/d) = DEE (kJ/d) - {[sleeping MR (kJ/min) × 1440 (min/d)] + [0.1 × DEE (kJ/d)]}.

⁵{DEE (kJ/d) × 0.9 - [sleeping MR (kJ/min) × 1440 (min/d)]/[reference activity MR (kJ/min) - sleeping MR (kJ/min)]}.

⁶{DEE (kJ/d) - [sleeping MR (kJ/min) × sleep duration (min/d)] - sedentary MR (kJ/min) × [1440 - sleep duration (min/d)]/[reference activity MR (kJ/min) - sedentary MR (kJ/min)]}.

adjustment for BW, walking MR remained 25% higher in the obese subjects than in the nonobese subjects ($P < 0.002$, data not shown). Finally, the walking physical activity ratio (PAR = walking MR/sleeping MR), on average, was significantly ($P < 0.001$) higher in the obese subjects than in the nonobese subjects (5.91 ± 0.14 compared with 3.89 ± 0.10).

The measured PAEE, as well as the estimated AEE₁ and AEE₂, were significantly ($P < 0.001$) higher in the obese subjects than in the nonobese subjects (Table 2). However, AEE₁ was higher than PAEE ($P < 0.001$), which indicates that AEE₁ overestimated EE associated with physical activities, and the difference was greater in the obese subjects than in the nonobese subjects ($P < 0.001$). AEE₂ also overestimated PAEE ($P < 0.001$), but the difference was smaller than with AEE₁ and did not vary significantly with obesity. After adjustment for BW, PAEE and AEE₂ were still significantly higher in the obese subjects than in the nonobese subjects (3.48 ± 0.085 compared with 3.01 ± 0.085 MJ/d, $P = 0.008$; and 3.79 ± 0.129 compared with 3.21 ± 0.129 MJ/d, $P = 0.033$, respectively), whereas AEE₁ did not differ significantly ($P = 0.190$).

The validity of the ARTE EE index could be checked by using the results obtained with the use of whole-body calorimetry. In addition to the 120 min of walking on a treadmill at 4, 5, and 6 km/h (mean speed: 5 km/h), subjects had ≈ 20 min of light physical activity for washing, dressing, and making the bed, which could be energetically equivalent to ≈ 7 –10 min of walking at 5 km/h. ARTE EE₁ was calculated by using sleeping MR as the basal EE and walking at 5 km/h as the reference activity. The results showed that ARTE EE₁ greatly overestimated physical activity: 176 and 221 min in the obese and nonobese subjects (for boys and girls combined), respectively, compared with 127–130 min of reference activity (walking at 5 km/h) as measured in the calorimeters ($P < 0.001$). In addition, the difference between the two measurements was smaller in the obese subjects than in the

nonobese subjects ($P < 0.001$). ARTE EE₂ gave values significantly different from the actual duration of physical activities in both the obese and the nonobese subjects ($P < 0.001$), although numerical values were close (Table 2).

Individual relations to assess energy expenditure in free-living conditions

The best-fitting equations between EE and HR as recorded in the whole-body calorimeters during 24 h were obtained by using a polynomial relation of the third order (35). The coefficient of determination (R^2) averaged 0.95, and the residual SD was 2.17 kJ/min for all activities. A better estimation of DEE was obtained by using the polynomial relations for physical activities and the 2 linear relations established during sleeping and sedentary activities, respectively. The difference between DEE estimated by using the 3 types of relations calculated for each individual (for physical, sleeping and sedentary activities, respectively) and DEE measured in the whole-body calorimeters was -96 ± 70 kJ (or -0.7%). Consequently, the 3 relations calculated for each subject were used to estimate DEE from HR recordings in free-living conditions.

Energy expenditure and time devoted to the main activities in free-living conditions

DEEs in free-living conditions were 2.26 MJ higher in the obese subjects than in the nonobese subjects ($P < 0.001$, Table 3) but did not differ significantly after adjustment for FFM ($P > 0.95$). The physical activity level calculated by using PAL = DEE/(sleeping MR × 1440) was significantly higher in the obese subjects than in the nonobese subjects (1.66 ± 0.02 compared with 1.55 ± 0.02 , $P < 0.05$).

Sleeping MR and the metabolic rates for sedentary activities (leisure seated activities, schoolwork, and meals) were significantly higher in the obese subjects than in the nonobese subjects

TABLE 3

Energy expenditure (EE) of adolescents as measured in free-living conditions and assessed by using several physical activity indexes¹

	Boys		Girls		P		
	Nonobese (n = 23)	Obese (n = 13)	Nonobese (n = 27)	Obese (n = 14)	Obesity	Sex	Obesity × sex interaction
Sleeping MR (kJ/min)	4.93 ± 0.178	5.52 ± 0.178	4.27 ± 0.178	4.96 ± 0.178	0.001	0.001	0.765
Leisure seated activities MR (kJ/min)	7.44 ± 0.311	10.48 ± 0.311	6.40 ± 0.311	9.28 ± 0.311	0.001	0.001	0.813
School and homework MR (kJ/min)	8.23 ± 0.318	9.45 ± 0.318	6.68 ± 0.318	8.46 ± 0.318	0.001	0.001	0.406
Meals MR (kJ/min)	8.31 ± 0.324	10.48 ± 0.324	7.00 ± 0.324	9.21 ± 0.324	0.001	0.001	0.950
Miscellaneous activities MR (kJ/min)	8.95 ± 0.398	11.04 ± 0.398	7.77 ± 0.398	10.10 ± 0.398	0.001	0.013	0.768
Light physical activities MR (kJ/min)	11.58 ± 0.544	17.37 ± 0.544	9.32 ± 0.544	15.39 ± 0.544	0.001	0.001	0.798
Moderate physical activities MR (kJ/min)	14.39 ± 1.165	30.60 ± 1.165	14.10 ± 1.165	25.86 ± 1.165	0.001	0.136	0.188
Sports MR (kJ/min)	24.83 ± 1.211	23.25 ± 1.211	18.26 ± 1.211	19.88 ± 1.211	0.988	0.001	0.247
DEE (kJ/d)	11.26 ± 0.457	13.41 ± 0.457	9.38 ± 0.457	11.74 ± 0.457	0.001	0.001	0.851
PAEE (kJ/d) ²	3.86 ± 0.287	3.98 ± 0.287	3.13 ± 0.287	3.22 ± 0.287	0.737	0.016	0.954
AEE ₁ (kJ/d) ³	4.12 ± 0.268	5.47 ± 0.268	3.23 ± 0.268	4.60 ± 0.268	0.001	0.003	0.971
AEE ₂ (kJ/d) ⁴	3.00 ± 0.229	4.13 ± 0.229	2.30 ± 0.229	3.43 ± 0.229	0.001	0.005	0.996
ARTE EE ₁ (min/d) ⁵	222 ± 16.0	138 ± 16.0	204 ± 16.0	121 ± 16.0	0.001	0.244	0.978
ARTE EE ₂ (min/d) ⁶	131 ± 22.4	77 ± 22.4	112 ± 22.4	60 ± 22.4	0.010	0.378	0.953

¹Least squares $\bar{x} \pm SE$. MR, metabolic rate; DEE, daily EE; PAEE, physical activity EE; AEE, activity EE; ARTE, activity-related time equivalent. Significance by ANOVA of the main effects of obesity and sex and for obesity × sex interaction.

²PAEE (kJ/d) = DEE (kJ/d) - [sleeping EE (kJ/d) + sedentary EE (kJ/d)].

³AEE₁ (kJ/d) = DEE (kJ/d) - [sleeping MR (kJ/min) × 1440 (min/d)].

⁴AEE₂ (kJ/d) = DEE (kJ/d) - {[sleeping MR (kJ/min) × 1440 (min/d)] + [0.1 × DEE (kJ/d)]}.

⁵{DEE (kJ/d) × 0.9 - [sleeping MR (kJ/min) × 1440 (min/d)]/[reference activity MR (kJ/min) - sleeping MR (kJ/min)]}.

⁶{DEE (kJ/d) - [sleeping MR (kJ/min) × sleep duration (min/d)] - sedentary MR (kJ/min) × [1440 - sleep duration (min/d)]/[reference activity MR (kJ/min) - sedentary MR (kJ/min)]}.

($P < 0.001$, Table 3). After adjustment for FFM, sleeping MR did not differ significantly between the obese and the nonobese subjects, but the MR for leisure seated activities was still higher in the obese subjects (8.89 compared with 7.45 kJ/min, $P < 0.001$). Similarly, the PARs of leisure seated activities, schoolwork, and meals were significantly higher in the obese subjects than in the nonobese subjects (1.81 ± 0.02 compared with 1.58 ± 0.02, $P < 0.0001$; 1.70 ± 0.02 compared with 1.62 ± 0.02, $P < 0.02$; and 1.88 ± 0.03 compared with 1.67 ± 0.03, $P < 0.001$, respectively), which is contrary to the results obtained in the whole-body calorimeters. According to the teachers of the obese adolescents, this could be due to the greater restlessness of the obese adolescents housed in groups at the institution than of the nonobese adolescents living at home.

The time spent sleeping was longer for the obese subjects than for the nonobese subjects (569 ± 8 compared with 546 ± 6 min/d, $P < 0.02$). However, the time spent at school and doing homework was 78 min/d less for the obese adolescents than for the nonobese adolescents ($P < 0.001$, **Figure 1**) because the obese subjects did not have homework at the beginning of the school year. The spare time was spent playing board games. Consequently, EE associated with leisure seated activities was twice as much in the obese subjects than in the nonobese subjects ($P < 0.001$, Figure 1).

Miscellaneous activities MR was higher in the obese adolescents than in the nonobese adolescents ($P < 0.001$, Table 3), but it was significantly lower after adjustment for BW (7.67 compared with 9.95 kJ/min, $P < 0.001$). Similarly, miscellaneous activities EE was significantly ($P < 0.001$) higher in obese adolescents than in nonobese adolescents (Figure 1). However, time spent in light physical activities (eg, shopping, slow walking, housework, recreation) was 47 min/d longer in the obese adolescents than in the nonobese adolescents ($P < 0.001$). The MR for light physical activities was 5.9 kJ/min higher in the obese subjects than in the

nonobese subjects ($P < 0.001$, Table 3), but it did not differ significantly after adjustment for BW ($P = 0.465$). The PAR was also significantly ($P < 0.001$) higher in the obese subjects than in the nonobese subjects (3.13 ± 0.07 compared with 2.30 ± 0.05). Consequently, EEs corresponding to light physical activities were 2.5 times higher in the obese subjects than in the nonobese subjects ($P < 0.001$, Figure 1).

In contrast, time devoted to moderate physical activities (walking at own speed, recreational activities at a low intensity) was much less in the obese adolescents than in the nonobese adolescents (6 ± 6 compared with 59 ± 4 min/d, $P < 0.001$). However, the MR (kJ/min) was twice as high in the obese subjects than in the nonobese subjects ($P < 0.001$), and it was 54% higher after adjustment for BW ($P < 0.001$). The PAR was also much higher in the obese subjects than in the nonobese subjects (5.55 ± 0.29 compared with 3.12 ± 0.14, $P < 0.001$).

Nevertheless, EE corresponding to moderate physical activities was 0.66 MJ/d lower in the obese subjects than in the nonobese subjects ($P < 0.001$). In the same way, EE corresponding to sports (physical education classes, physical training, and athletic competitions) in the obese subjects amounted to 25% of that in the nonobese adolescents ($P < 0.001$, Figure 1). This resulted mainly from the shorter time devoted to sports activities (13 ± 4 compared with 44 ± 3 min/d, $P < 0.001$), because the sports activities MR did not differ significantly between the obese and nonobese subjects (Table 3). However, after adjustment for BW, the MR for sports activities was 44% lower in the obese subjects than in the nonobese subjects (14.1 compared with 24.9 kJ/min, $P < 0.001$).

EE corresponding to physical activities (PAEE) did not differ significantly between the obese and nonobese subjects, whereas AEE₁ and AEE₂ were 1.36 and 1.13 MJ/d, respectively, higher in the obese adolescents than in the nonobese adolescents ($P < 0.001$,

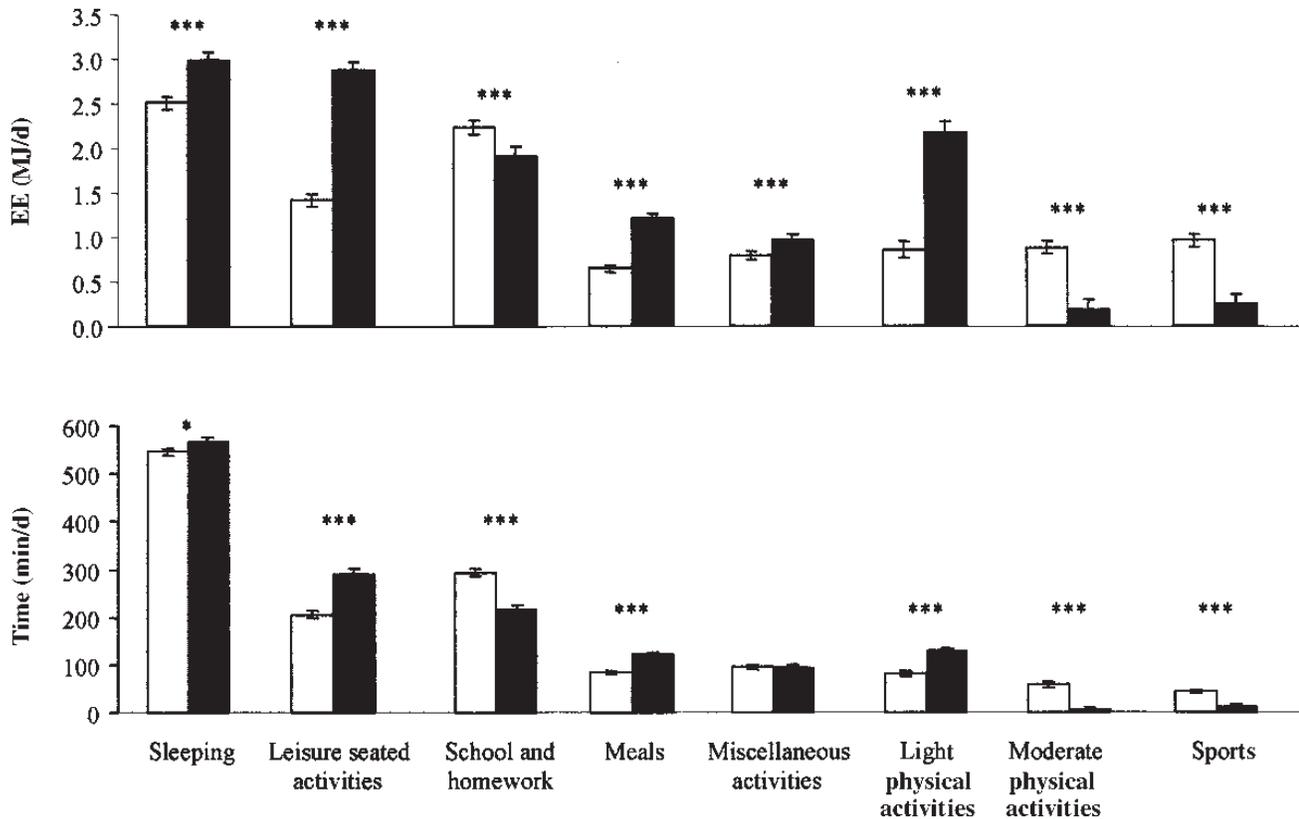


FIGURE 1. Least-squares mean (\pm SE) energy expenditure (EE) of and time devoted to the main activities by nonobese (\square ; $n = 50$) and obese (\blacksquare ; $n = 27$) adolescents in free-living conditions. Significant effects of obesity: * $P < 0.05$, *** $P < 0.001$.

Table 3). ARTE EE₁ corresponded to 129 and 213 min of walking at 5 km/h in the obese and nonobese subjects, respectively, compared with 19 and 103 min of moderate activities plus sports activities. However, ARTE EE₂ gave lower and more reliable figures for physical activity that were similar to figures for the duration of moderate activities and sports activities in the nonobese subjects. ARTE EE₂ was significantly ($P < 0.01$) lower in the obese adolescents than in the nonobese adolescents (69 compared with 122 min/d, Table 3).

Effects of sex on energy expenditure and physical activity

In standardized conditions, BMR, sleeping MR, and sedentary MR were 12–14% higher in the boys than in the girls ($P < 0.001$, Table 2), and after adjustment for FFM, they were 8–9% higher ($P < 0.001$). Similarly, walking MR, PAEE, and AEE₁ were 9% higher in the boys than in the girls ($P < 0.03$), even after adjustment for BW ($P < 0.01$, data not shown). AEE₂ tended to be higher in the boys than in the girls in absolute values ($P = 0.073$) and was 8.6% higher after adjustment for BW ($P < 0.05$). However, ARTE EE₁ and ARTE EE₂ did not differ significantly between the boys and the girls.

In free-living conditions, the effect of sex on sleeping MR and sedentary MR was the same as that in standardized conditions. In contrast, the duration of moderate physical activities was significantly ($P < 0.05$) greater in the boys than in the girls (41 ± 5 compared with 23 ± 5 min/d), but MR was not significantly different. The duration of sports activities did not differ significantly between the boys and the girls, but the MR was 26.5% higher in

the boys than in the girls (Table 3), even after adjustment for BW (21.8 compared with 17.2 kJ/min, $P < 0.001$). Finally, PAEE, AEE₁ and AEE₂ were significantly higher in the boys than in the girls, even after adjustment for BW ($P < 0.02$), whereas ARTE EE₂ did not differ significantly by sex.

DISCUSSION

This study provides new information on EE partitioning between sedentary and physical activities in obese and nonobese adolescents. DEE and activity patterns of obese children aged 7–10 y with a high percentage of FM (32–42%) were determined in several studies (10, 11, 14, 20), but information on adolescents is scarce (9). In addition, the present study enabled the comparison of time spent at various sedentary and physical activities, their energy costs (ie, MR), and the corresponding EE in severely obese and nonobese adolescents of both sexes in standardized and in free-living conditions, both before and after adjustment for FFM or BW.

DEE and the MRs for various sedentary and physical activities, as measured in the whole-body calorimeters with the same activities program, were significantly higher in the obese subjects than in the nonobese subjects. After adjustment for FFM, however, BMR, sleeping MR, and the MR and PAR of sedentary activities did not differ significantly between the obese adolescents and the nonobese adolescents, which is in agreement with the results of previous studies (9, 10, 37, 38). The MRs and PARs of walking at the same

speeds on a treadmill were much higher in the obese subjects than in the nonobese subjects. Furthermore, after adjustment for BW, the energy cost of walking at the same speed and the consequent PAEE were $\approx 25\%$ higher in the obese subjects than in the nonobese subjects, which is contrary to the results obtained in younger and less obese children (20). The current result could be explained by the greater difficulty of walking for these severely obese adolescents, because the difference in energy cost of walking between the obese and nonobese subjects increased with speed. Walking at 5 km/h corresponded, on average, to 59.1% and 42.2% $\dot{V}O_{2\max}$ in the obese and nonobese subjects, respectively ($P < 0.001$; Lazzar S et al, unpublished observations, 2002). Finally, for the same activity program, physical activity level was significantly higher in the obese subjects than in the nonobese subjects, and DEE adjusted for FFM was also higher because of the higher energy cost of walking.

In free-living conditions, DEE and physical activity level were significantly higher in the obese subjects than in the nonobese subjects. However, DEE adjusted for FFM did not differ significantly between the obese subjects and the nonobese subjects, which is in agreement with the results of other studies (9, 11, 14). Physical activity EE (light and moderate activities and sports) did not differ significantly between the obese and nonobese subjects but was 61% lower in the obese subjects after adjustment for BW. It accounted for 21% and 28% of DEE in the obese and nonobese adolescents, respectively.

The obese adolescents spent more time at light physical activities, especially shopping or slow walking during the weekend, than did the nonobese subjects, but much less time at moderate physical activities. The energy costs and the PARs of light and moderate physical activities were higher in the obese subjects than in the nonobese subjects and were associated with higher percentages of $\dot{V}O_{2\max}$: 29.8% and 52.0% compared with 25.3% and 34.8%, respectively (Lazzar S et al, unpublished observations, 2002). Nevertheless, the EE of the obese subjects during moderate physical activities amounted to 20% of that of the nonobese subjects. Time devoted to sports activities by the obese subjects amounted to 30% of that for the nonobese subjects because the former group had only physical education classes at school, whereas 62% of the nonobese subjects also had physical training and athletic competitions. Interestingly, the energy cost of physical education classes did not differ significantly between the obese and nonobese subjects, but it was much lower in the obese subjects after adjustment for BW, which suggests that they were less active than were the nonobese subjects. This assumption is supported by the fact that sports activities corresponded to 38.7% $\dot{V}O_{2\max}$ (less than for moderate activities) in obese subjects compared with 51.0% in nonobese subjects ($P < 0.001$; Lazzar S et al, unpublished observations, 2002). EE during moderate physical activities and sports in the obese subjects was, on average, 24% of that in the nonobese subjects (0.45 compared with 1.85 MJ/d), and it contributed to 13% of PAEE in the obese subjects compared with 53% of PAEE in the nonobese subjects.

The activities of these obese and nonobese adolescents were not analyzed in exactly the same conditions because the former were institutionalized, whereas the latter were at home. However, at their specialized institution, the obese subjects had free access to outdoor activities (eg, basketball, volleyball, badminton) and indoor physical (eg, table tennis, swimming) and sedentary (eg, television, video games, board games) activities. In addition, one afternoon/wk, they walked (as a group) or played volleyball for 1 h. At home during the weekend, the obese adolescents spent

most of their time watching television, while seated or reclining, and playing video games; their main physical activity was shopping for 1–2 h with their parents. Their activities were similar during the 2-wk holidays spent at home in October and at Christmas (unpublished data). Thus the activities recorded during the period of control were probably representative of their usual activities.

One of the main questions we wanted to examine was the relevance of indexes of physical activity in obese and nonobese subjects in free-living conditions. Measurements of DEE and EE corresponding to sleeping, sedentary, and physical activities in the whole-body calorimeters enabled us to validate the AEE and ARTE EE indexes. AEE₁ overestimated EE associated with physical activities, especially in the obese subjects, even after adjustment for BW. This could be explained by the fact that AEE₁ includes "sedentary MR – BMR," which is higher in obese subjects than in nonobese subjects because of their higher FFM. The discrepancy was less with AEE₂ because the correction for TEF (10% of DEE) compensated for part of "sedentary MR – BMR" during the period of being awake. However, calculations based on the calorimetric data presented in Table 2 showed that AEE₁ overestimates PAEE whatever the physical activity, whereas AEE₂ greatly overestimates low PAEE but underestimates high PAEE (Figure 2). In other respects, ARTE EE enables comparisons of subjects of different BWs and different exercise energy economics (18, 19). Nevertheless, ARTE EE₁ greatly overestimated physical activity, especially in the nonobese subjects, because the increase in EE (above sleeping MR) during sedentary activities

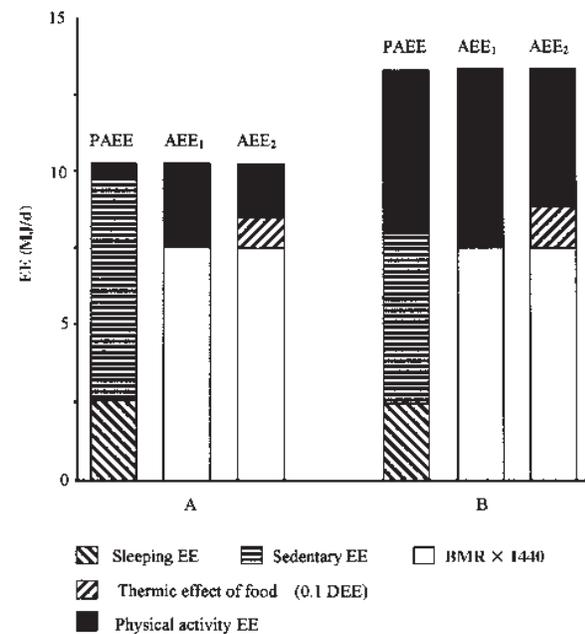


FIGURE 2. Diagrammatic partition of energy expenditure (EE) of nonobese boys depending on physical activity: 0.5 h moderate activity (A) or 4 h medium-intensity activity (B). BMR, basal metabolic rate; DEE, daily EE. Physical activity EE as measured by whole-body calorimetry: PAEE (MJ/d) = DEE (MJ/d) – [sleeping EE (MJ/d) + sedentary EE (MJ/d)]. Estimated activity EE: AEE₁ (kJ/d) = DEE (kJ/d) – [BMR (kJ/min) × 1440 (min/d)]; AEE₂ (kJ/d) = DEE (kJ/d) – {[BMR (kJ/min) × 1440 (min/d)] + [0.1 × DEE (kJ/d)]}. AEE₁ overestimates PAEE whatever the physical activity, whereas AEE₂ overestimates low PAEE but underestimates high PAEE.

was considered to result from physical activity. ARTE EE₂ was corrected for this bias, which resulted in estimates of physical activity close to the actual duration of walking in both the obese and nonobese subjects. In addition, ARTE EE₂ corresponded to the increase in EE above sedentary EE during walking.

The validity of ARTE EE₂ to assess the physical activity of obese and nonobese subjects in free-living conditions when DEE is determined by the doubly labeled water method and BMR by indirect calorimetry has been tested. Replacing BMR with sleeping MR reduced ARTE EE₂ by 5 and 8 min in the obese and nonobese subjects, respectively. A 30-min error in the estimation of sleep duration (540 rather than 510 min) caused errors of 3.8 and 7.4 min in ARTE EE₂ for the obese and nonobese subjects, respectively. In addition, a 0.05 BMR error in the estimation of sedentary EE (PAR = 1.55 rather than 1.50) caused errors of -11.6 and -22.9 min in ARTE EE₂ for the obese and nonobese subjects, respectively. Thus, ARTE EE₂ can be used satisfactorily to assess physical activity in obese and nonobese subjects when DEE and BMR are known.

In free-living conditions, AEE₁ and AEE₂ were higher in obese subjects than in nonobese subjects, which is in agreement with earlier results obtained in obese and nonobese children and adolescents (9, 11–14, 17). However, AEE₁ and ARTE EE₁ overestimated physical activity, because the ARTE to walking at 5 km/h was higher than the total time spent at light, moderate, and sports activities, especially in the nonobese subjects (212 and 213 compared with 185 min/d). By contrast, ARTE EE₂ gave more reliable figures for physical activity, because they corresponded to the sum of the time spent at moderate and sports activities plus 23% and 39% of the time spent at light physical activities by the nonobese and the obese subjects, respectively.

In conclusion, DEEs, MRs, and EEs corresponding to the various sedentary and physical activities as measured by whole-body indirect calorimetry with the same activity program were significantly higher in the obese subjects than in the nonobese subjects, but none except walking was significantly different after adjustment for FFM or BW. In free-living conditions, the obese subjects spent more time at light physical activities but much less time at moderate and sports activities than did the nonobese subjects. The MR (kJ/min) for sports activities did not differ significantly, which indicates that the obese subjects engaged in less intense activities; consequently, the EEs of the obese subjects for moderate and sports activities amounted to 20% and 25% of those of the nonobese subjects, respectively.

AEE and ARTE EE₁ overestimated physical activity in both the obese and nonobese subjects, as shown by the calorimetric data, because the increase in MR (above sleeping MR or BMR) during sedentary activities was considered to result from physical activity. However, ARTE EE₂, as validated by using the calorimetric data, gave reliable and satisfactory estimates of physical activity in free-living conditions when DEE and BMR were known. 

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All authors participated in the design and implementation of the experimental protocol and in the discussion of results. SL and AB performed most of the measurements and data analyses. SL also drafted the manuscript. CM was responsible for calorimetric measurements, and JV was responsible for statistical analysis. MM was in charge of obese adolescents and recruited the vol-

unteers. YB participated in the supervision of the study and revision of the manuscript. MV was responsible for all stages of the study, participated in measurements and interpretation of results, and revised the manuscript. None of the authors had a conflict of interest with regard to this study.

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