Pubertal alterations in growth and body composition. V. Energy expenditure, adiposity, and fat distribution

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Divisions of Endocrinology and Metabolism, Departments of 1Pediatrics, 3Human Services, 4Medicine, and 5Pharmacology and 6Health Evaluation Sciences, University of Virginia Health Sciences Center, Curry School of Education, University of Virginia, Charlottesville, Virginia 22908

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Roemmich, James N., Pamela A. Clark, Kim Walter, James Patrie, Arthur Weltman, and A. D. Rogol. Pubertal alterations in growth and body composition. V. Energy expenditure, adiposity, and fat distribution. Am J Physiol Endocrinol Metab 279: E1426–E1436, 2000.—We determined whether activity energy expenditure (AEE, from doubly labeled water and indirect calorimetry) or physical activity (7-day physical activity recall (PAR)) was more related to adiposity and the validity of PAR estimated total energy expenditure (TEE_PAR) in prepubertal and pubertal boys (n = 14 and 15) and girls (n = 13 and 18). AEE, but not physical activity hours, was inversely related to fat mass (FM) after accounting for the fat-free mass, maturation, and age (partial r = −0.35, P ≤ 0.01). From forward stepwise regression, pubertal maturation, AEE, and gender predicted FM (r² = 0.36). Abdominal visceral fat and subcutaneous fat were not related to AEE or activity hours after partial correlation with FM, maturation, and age. When assuming one metabolic equivalent (MET) equals 1 kcal·kg body wt·h⁻¹, TEE_PAR underestimated TEE from doubly labeled water (TEE bias) by 555 kcal/day ± 2 SD limits of agreement of 913 kcal/day. The measured basal metabolic rate (BMR) was >1 kcal·kg body wt·h⁻¹ and remained so until 16 yr of age. TEE bias was reduced when setting 1 MET equal to the measured (bias = 60 ± 51 kcal/day) or predicted (bias = 53 ± 50 kcal/day) BMR but was not consistent for an individual child (± 2 SD limits of agreement of 784 and 764 kcal/day, respectively) or across all maturation groups. After BMR was corrected, TEE bias remained greatest in the prepubertal girls. In conclusion, in children and adolescents, FM is more strongly related to AEE than activity time, and AEE, pubertal maturation, and gender explain 36% of the variance in FM. PAR should not be used to determine TEE of individual children and adolescents in a research setting but may have utility in large population-based pediatric studies, if an appropriate MET value is used to convert physical activity data to TEE data.

As the prevalence of obesity in North American children and adolescents continues to rise (43), a better understanding of the causes and effective treatment of childhood obesity becomes increasingly important. A decline in dietary fat, a stable energy intake, and stable energy expenditure via basal metabolism (basal metabolic rate (BMR)) and the thermic effect of food (TEF) over the past four decades suggest that a reduction in physical activity energy expenditure (AEE) is responsible for the increased number of obese youth (43, 44).

An accurate method of assessing free-living AEE of youth is to calculate the difference between the total energy expenditure (TEE) measured by doubly labeled water (DLW) and BMR measured by indirect calorimetry. However, DLW provides no information with regard to the intensity or duration of physical activity, which may be more important in influencing the adiposity of children than AEE (20, 44). The 7-day physical activity recall (PAR) gives qualitative information regarding the intensity, frequency, and duration of the physical activity (36, 37).

Currently, it is unclear if the time spent in sedentary activity (11, 27), the time spent in physical activity (20), or AEE is most related to the adiposity of children and adolescents. Studies using methods of varying accuracy to assess the relationship between AEE and body composition have found an inverse relationship (10, 15, 45). Others have reported very weak relationships (18, 20, 21, 23). Investigations using accurate methods of assessing free-living AEE are needed to better understand the causes of rising childhood obesity.

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measures of activity, energy expenditure, and body composition are required to determine the relationships among them.

Although accurate methods are necessary to describe interactions between energy expenditure and adiposity and to establish the efficacy of behavioral and lifestyle interventions to increase the energy expenditure of children, few valid methods of estimating energy expenditure exist. The DLW method is accurate and valid but often is prohibitively expensive and cumbersome because the children are required to collect several urine samples over a 2-wk period (17). Additionally, a prolonged world-wide shortage of H$_2$O has made the measurement of TEE by DLW impossible for even small groups of children. Self-report measures such as PAR have been developed for this purpose. It is simple, inexpensive, and well accepted by children. The physical activity times and intensities obtained by PAR have been used to estimate TEE (3, 4, 36, 38). However, no study has compared TEE from DLW (TEE$_{DLW}$) with TEE estimated from PAR (TEE$_{PAR}$). Therefore, the purpose was to determine whether AEE, total activity time, or the number of hours spent in activities of various intensities was most related to criterion estimates of body composition and abdominal fat distribution of prepubertal and pubertal boys and girls. We also determined the agreement between TEE$_{DLW}$ and TEE$_{PAR}$ and examined the influence of age, gender, TEE, and percentage of body fat (%fat) on the degree of agreement.

METHODS

Subjects

Prepubertal and pubertal boys ($n = 14$ and $n = 15$) and girls ($n = 13$ and $n = 18$) with normal weight, height, and weight-for-height enrolled in a longitudinal growth study were evaluated in a cross-sectional manner. Subjects were placed into pubertal groups based on Tanner’s criteria (40) as were evaluated in a cross-sectional manner. Subjects were weight-for-height enrolled in a longitudinal growth study.

BMR was measured for 30 min via indirect calorimetry (Deltatrac; SensorMedics, Yorba Linda, CA). Subjects were assessed upon waking. We have previously reported the within-day test-retest reliability (intraclass correlation = 0.98) of this measure in our laboratory (33).

TEE was measured by DLW. The subjects consumed a mixed oral dose of 99.9% enrichment $^{2}$H$_2$O (0.05 g/kg) and 10% enrichment H$_2$O (1.5 g/kg). Urine samples were collected immediately before dosing (0800) and at 4 h, 5 h, 1 day, 6 days, and 12 days after dosing. All urine samples were collected between 0800 and 1200 and were kept frozen at $-20^\circ$C in cryovials until analysis by isotope ratio mass spectrometry (Europa Hydra 20/20 gas isotope ratio mass spectrometer (GIRMS); Metabolic Solutions, Merrimack, NH). Deuterium analysis was completed after a 72-h equilibration with CO$_2$. Differences in $^2$H and $^{18}$O in the pre- and postdose urine samples were determined using the unprocessed mass spectrometric data as previously described (31). The unprocessed mass spectrometric (enrichment) data were standardized by expressing it as a fraction of the initial dose as suggested by the consensus report of the International Dietary Energy Consultancy Group (31). Linear regression was used to determine the slope and intercept of the linear relationship between the time in days and the normalized $^2$H and $^{18}$O data. The pool sizes for $^{2}$H$_2$O ($N_p$) and H$_2$O ($N_o$) were estimated from the reciprocals of the regression intercepts. The intercept of the regression line was the $N_p$ to-$N_o$ ratio ($N_p/N_o$). The data points were analyzed, and the observed outliers in the data were reanalyzed. The fractional turnover rates of $^2$H and $^{18}$O were determined from the slope of the regression line. Any $N_p/N_o$ lying outside the range of 1.015 and 1.06 were reanalyzed. If the regression outliers or $N_p/N_o$ were confirmed upon reanalysis, the data were not used. The mean daily rate of CO$_2$ production (mol/day) was calculated by the revised equations of Speakman et al. (39). The mean daily energy expenditure was calculated by multiplying the rate of CO$_2$ production by 127.5 kcal/mmol CO$_2$, the energy equivalent of the typical Western diet that will produce a respiratory quotient of 0.85, with 15% of energy from protein oxidation (31).

Quality control data: Precision data. Quality control data were obtained from Metabolic Solutions. A method validation is repeated every 6 mo to establish the precision and accuracy for the $^2$H and $^{18}$O measures using internal laboratory standard assigned values vs. international standards (VSMOW). The data are reported as delta VSMOW. To determine interday $^{18}$O precision, seven standards ranging in value from about $-9$ to 200 delta were analyzed multiple times over multiple days. Each of the seven standards must have a relative standard deviation (RSD = coefficient of variation x 100) $\leq$2.5. Interday $^2$H precision was determined by measuring seven standards ranging in value from about $-50$ to 3,000 delta multiple times over multiple days. For each standard, RSD must be $\leq$2.5 except for the $-50$ delta standard whose RSD must be $<10$. To determine intraday $^{18}$O and $^2$H precision, within each run, four quality control standards are analyzed 5 to 10 times, and their mean values must fall within the RSD range. The $^{18}$O means and RSD limits (in parentheses) were $-8.69$ per mil (1.99), $36.05$ per mil (1.33), $10.89$ per mil (0.81), and $210.10$ per mil (0.46). The $^2$H means and RSD limits were $-53.03$ per mil ($<15$), $564.74$ per mil ($<2$), $1,447.03$ per mil ($<2$), and $3,022.35$ per mil ($<2$). If the interday or intraday precision data did not meet specifications, the analysis run was not accepted, and the samples were either reassayed or prepared again (Metabolic Solutions).

Quality control data: Accuracy data. During the method validation studies, two international standards [International Atomic Energy Agency (IAEA) $^{18}$O and $^2$H standards] were measured in multiple runs on multiple days. The IAEA range (95% confidence interval) for $^{18}$O is typically $+3$–$5$ delta per mil and for $^2$H typically $5$–$10$ delta per mil. The instruments were accepted as performing properly when the $^{18}$O and $^2$H results were within $\pm 0.5$ delta of their respective IAEA standards. For both $^{18}$O and $^2$H, the intraday accuracy was maintained through the secondary standards (standards 1–4) because of the scarcity of the IAEA standards.

In a comparison of 18 prominent laboratories assaying DLW, Metabolic Solutions Laboratory had an error of 5.9%. The median error of all laboratories was 6.6% (32).

AEE was estimated by subtracting the BMR from TEE. As discussed by Goran et al. (20) and Crocker and Algina (9), estimates based on the difference between two scores were
subject to error propagation. As such, true scores, which take into account the test-retest reliability of TEE and BMR measures, were calculated (9). True scores improve the precision of an estimate that is based on the difference between two measures but does not change the group mean data (20). When calculating the “true” scores, a Pearson correlation coefficient of 0.8 was used for BMR data and 0.6 for TEE data (20). The true scores were used to estimate AEE as follows: (true TEE × 0.90) – true BMR. The 10% correction of TEE was to account for the energy expenditure of the thermogenic effect of food (29).

Seven-Day PAR

The time spent in physical activity at different intensities was assessed with PAR (3, 4, 36, 38). All subjects were interviewed by the same investigator (Roemmich) to recall the time spent in sleep (1 metabolic equivalent [MET]) and in moderate (4 METs, as strenuous as walking), hard (6 METs, an intensity between walking and running), and very hard (10 METs, as strenuous as running) activities. The greatest amount of time each day is spent in light activities (1.5 METs, less strenuous than walking, not including sleeping) and was determined by subtraction. A MET is a multiple of the resting energy expenditure. Before the interview, the subjects were given instructions on how to properly answer the interviewer’s questions. The interview began with the previous day and worked back the preceding 6 days. To aid recall, the subjects were prompted for activities in the morning, noon, and evening of each day. TEE was calculated by multiplying the number of hours at each intensity by its respective MET value, assuming that 1 MET was equivalent to 1 kcal·kg body wt·h⁻¹. The data are presented as kilocalories per day rather than kilocalories per kilogram body weight per day because the farther the resting metabolism differs from 1 kcal·kg body wt·h⁻¹, the more estimates of energy expenditure reflect the body weight than the metabolic rate (1). Procedures for estimating TEEPAR have been described previously (3, 36).

Body Composition

Body composition was estimated using a four-compartment model described by Lohman (25). We have described and validated the use of this model in our laboratory (34). Body density was measured by underwater weighing and corrected for residual lung volume by nitrogen washout. The body density was corrected for the total body water by deuterium oxide dilution and bone mineral content by dual-energy X-ray absorptiometry (QDR 2000; Hologic, Waltham, MA).

Body Fat Distribution

As previously described (33), the abdominal subcutaneous fat (ASF) and visceral fat (AVF) were measured at the L₁-L₅ intervertebral space with magnetic resonance imaging using a Siemens Vision 1.5T scanner. Tissue areas were assessed using a Dixon imaging sequence phase corrected for magnetic field inhomogeneities. A standard spin-echo pulse sequence was used for the in-phase image. The out-of-phase image was acquired by shifting the 180° refocusing pulse by 1.12 ms. Images were acquired with a slice thickness of 6 mm, matrix of 256 × 256, and a ratio of repetition time to echo time of 575/15 ms. For postacquisition processing, a magnetic field inhomogeneity map was calculated from the in-phase and out-of-phase images, which assumes that there are unequal amounts of fat and water in each pixel. This map was then used to unwrap phase shifts induced by the inhomogeneities using a region growing technique and was used to correct for phase error in the opposed phase image. Adding or subtracting the in-phase and opposed phase images resulted in the water and fat images, respectively. The fat- and water-based tissue areas were determined using MedX Software (Sensor Systems, Sterling, VA).

Statistics

Univariate 2 (gender) × 2 (maturation) ANOVA and covariance were used to compare group means for physical characteristics, energy expenditure, and physical activity. Simple and partial correlation analyses were used to examine the associations among gender, maturation, AEE, activity hours, body composition, and body fat distribution. Forward stepwise regression was used to determine the combination of variables that most accurately predicted fat mass (FM) and fat distribution in our sample, with careful attention to multicollinearity among variables. TEEPAR was compared with TEEDLW using the Bland and Altman (5) method. Ordinary least squares (OLS) regression analyses were used to test if the slopes and intercepts of the energy expenditure-adiposity relationships differed among the subject groups and to predict the bias in TEE as a linear function of age, gender, TEE, and percentage body fat (%fat). Goodness of the model fit was based on an internal bootstrap validation (22). The bootstrap method determines the precision of a statistic. Much more confidence can be placed on the value of R² from a bootstrap technique, where the model has been simulated, in our case, 400 times. The R² that is obtained from the bootstrap provides a more accurate estimate of the amount of variation in the response that we would expect to be able to explain if the original regression model were fit to a new sample of data. OLS was also used for the extra sum of squares (SS) F-test (28). Initially, TEE was predicted as a linear function of BMR, height, and weight. The five PAR variables (hours spent in sleep and light, moderate, hard, and very hard activities) were then added to the OLS model to determine if the combined information of these five variables significantly reduced the error sum of squares, where F = ([SS error(reduced model) – SS error(full model)])/Δdf/mean squared error(full model), where Δdf indicates degrees of freedom.

RESULTS

Physical Characteristics and Energy Expenditure

As shown in Table 1, the boys were taller (P = 0.02) and had a smaller FM (P = 0.04) and percentage body fat (%fat, P = 0.002) and a greater TEEDLW (P = 0.01) than the girls. As expected, the pubertal boys and girls were older (P < 0.001), taller (P < 0.001), heavier (P < 0.001), and had a greater FM (P = 0.002), fat-free mass (FFM; P < 0.001), AVF (P = 0.05), ASF (P = 0.07), and TEEPLW (P < 0.001) than the prepubertal boys and girls. The pubertal boys had a greater BMR than the other groups (gender by maturation interaction, P = 0.04). The interaction effect for TEEDLW was P = 0.07. After covariance for FFM, BMR remained significant (P = 0.05), whereas TEEPLW was significant only for the main effect of gender (P = 0.055). AEE was not related to FFM (r = −0.04, P = 0.74) and therefore was not covaried for FFM.
Table 1. Physical characteristics, four-compartment model body composition, body fat distribution, aerobic fitness, and energy expenditure of the subjects

<table>
<thead>
<tr>
<th></th>
<th>Prepubertal Boys (n = 14)</th>
<th>Pubertal Boys (n = 14)</th>
<th>Prepubertal Girls (n = 13)</th>
<th>Pubertal Girls (n = 18)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age,† yr</td>
<td>10.9 ± 1.0</td>
<td>13.4 ± 1.2</td>
<td>10.2 ± 1.4</td>
<td>12.8 ± 1.9</td>
</tr>
<tr>
<td>Tanner stage</td>
<td>3.4 ± 0.2</td>
<td>3.4 ± 0.2</td>
<td>3.0 ± 0.0</td>
<td>2.6 ± 0.2</td>
</tr>
<tr>
<td>Height,‡ cm</td>
<td>143.1 ± 4.7</td>
<td>162.2 ± 12.1</td>
<td>136.6 ± 8.9</td>
<td>158.1 ± 9.1</td>
</tr>
<tr>
<td>Weight,† kg</td>
<td>34.8 ± 6.9</td>
<td>52.0 ± 11.4</td>
<td>34.7 ± 7.9</td>
<td>51.2 ± 9.0</td>
</tr>
<tr>
<td>Body fat,§ %</td>
<td>19.3 ± 7.3</td>
<td>18.4 ± 6.3</td>
<td>23.3 ± 5.9</td>
<td>25.6 ± 6.7</td>
</tr>
<tr>
<td>Fat mass,∥ kg</td>
<td>7.0 ± 4.3</td>
<td>9.6 ± 4.4</td>
<td>8.3 ± 3.3</td>
<td>13.2 ± 5.0</td>
</tr>
<tr>
<td>Fat-free mass,∥ kg</td>
<td>27.8 ± 3.7</td>
<td>42.5 ± 10.0</td>
<td>26.4 ± 5.3</td>
<td>37.8 ± 6.1</td>
</tr>
<tr>
<td>Abdominal visceral fat,∥ cm²</td>
<td>44.0 ± 20.9</td>
<td>62.8 ± 21.6</td>
<td>47.5 ± 19.9</td>
<td>49.4 ± 11.8</td>
</tr>
<tr>
<td>Abdominal subcutaneous fat,∥ cm²</td>
<td>68.2 ± 60.5</td>
<td>105.3 ± 74.3</td>
<td>100.9 ± 61.9</td>
<td>136.0 ± 92.4</td>
</tr>
<tr>
<td>TEE DLW,§ kcal/day</td>
<td>2,174 ± 63</td>
<td>2,555 ± 67</td>
<td>2,123 ± 57</td>
<td>2,237 ± 62</td>
</tr>
<tr>
<td>BMR,‡ kcal/day</td>
<td>1,245 ± 56</td>
<td>1,626 ± 78</td>
<td>1,217 ± 30</td>
<td>1,359 ± 38</td>
</tr>
<tr>
<td>Activity energy expenditure, kcal/day</td>
<td>712 ± 51</td>
<td>673 ± 56</td>
<td>693 ± 31</td>
<td>654 ± 35</td>
</tr>
</tbody>
</table>

Values are means ± SD; n, no. of subjects. TEE DLW, total energy expenditure (TEE) by the doubly labeled water (DLW) method; BMR, basal metabolic rate. *Significant gender effect. †Significant maturation effect. ‡Significant gender × maturation interaction.

Seven-Day PAR

The time spent in activities of various intensities, as assessed by PAR, are shown in Table 2. The boys (P = 0.02) and prepubertal subjects (P = 0.03) spent more time sleeping. The prepubertal boys spent less time in light activities and more time in very hard activities than the other groups (gender by maturation interaction P = 0.01 for both variables). Prepubertal girls spent less time in hard activities (gender by maturation interaction, P = 0.08) and activity hours (sum of moderate, hard, and very hard activity hours; gender by maturation interaction, P = 0.002) than prepubertal boys and pubertal girls.

Relationships Among AEE, Physical Activity, and Adiposity

AEE-adiposity relationships. AEE was inversely related to FM of all subjects and boys (Fig. 1) and both the prepubertal (r = −0.41, P = 0.03) and pubertal (r = −0.34, P = 0.05) groups. The slope of the AEE/FM relationship was greater (P = 0.02, Fig. 1) for the boys (−0.0125 kg FM/kcal AEE, or −27.7 kcal AEE/kg FM) than the girls (−0.0073 kg FM/kcal AEE, or −5.3 kcal AEE/kg FM) but did not differ between pubertal groups.

<table>
<thead>
<tr>
<th></th>
<th>Prepubertal Boys</th>
<th>Pubertal Boys</th>
<th>Prepubertal Girls</th>
<th>Pubertal Girls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sleep**†</td>
<td>10.1 ± 0.3</td>
<td>9.4 ± 0.3</td>
<td>9.4 ± 0.2</td>
<td>9.0 ± 0.2</td>
</tr>
<tr>
<td>Light activity‡</td>
<td>11.8 ± 0.5</td>
<td>13.2 ± 0.3</td>
<td>13.6 ± 0.3</td>
<td>13.0 ± 0.3</td>
</tr>
<tr>
<td>Moderate activity</td>
<td>0.6 ± 0.2</td>
<td>0.6 ± 0.1</td>
<td>0.5 ± 0.2</td>
<td>0.9 ± 0.2</td>
</tr>
<tr>
<td>Hard activity</td>
<td>0.7 ± 0.2</td>
<td>0.6 ± 0.1</td>
<td>0.4 ± 0.1</td>
<td>0.8 ± 0.2</td>
</tr>
<tr>
<td>Very hard activity‡</td>
<td>0.8 ± 0.2</td>
<td>0.3 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>0.4 ± 0.1</td>
</tr>
<tr>
<td>Total activity time‡</td>
<td>2.1 ± 0.4</td>
<td>1.4 ± 0.2</td>
<td>1.0 ± 0.2</td>
<td>2.0 ± 0.3</td>
</tr>
</tbody>
</table>

Values are means ± SE. Units are h/day. Total activity time, sum of moderate, hard, and very hard activity. *Significant gender effect. †Significant maturation effect. ‡Significant gender × maturation interaction.

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Regression models. Forward stepwise regression was used to determine the combination of energy expenditure and physical activity variables that most accurately predicted FM, AFV, and ASF. To maintain a proper subject-to-variable ratio, the independent vari-
ables were limited to those considered in our a priori hypothesis: gender, maturation, and AEE and those variables that were significantly related to the dependent variable in the simple correlation analyses. As shown in Table 4, increased FM was best estimated with increasing values of pubertal maturation, lower values of AEE, and the female gender. Very hard activity hours and BMR did not add to the prediction of FM. No energy expenditure or physical activity variable significantly predicted AVF. Only FM entered into the model to predict AVF ($R^2 = 0.11$, $P = 0.01$) and ASF ($R^2 = 0.66$, $P < 0.001$).

Validity of TEE by the 7-Day PAR

BMR of children and adolescents does not equal 1 kcal·kg body wt$^{-1}$·h$^{-1}$. Conversion of PAR data to energy expenditure data utilizes multiples of the resting energy expenditure, which is assumed to be 1 kcal·kg body wt$^{-1}$·h$^{-1}$ (3, 36). However, this was less than ($P < 0.001$) the mean measured BMR (1.35 ± 0.03 kcal·kg body wt$^{-1}$·h$^{-1}$). As shown in Fig. 2, BMR did not approach 1 kcal·kg body wt$^{-1}$·h$^{-1}$ until about 16 yr of age, and as such BMR expressed in kilocalories per kilogram body weight per hour was lower ($P < 0.001$) in the pubertal subjects (Table 5).

TEE bias when assuming 1 MET equals 1 kcal·kg body wt$^{-1}$·h$^{-1}$. When we assumed that 1 MET equals 1 kcal·kg body wt$^{-1}$·h$^{-1}$, TEE$_{PAR}$ was greater in the pubertal than prepubertal subjects (Table 5). As shown in Fig. 3A, TEE$_{PAR}$ underestimated the criterion TEE$_{DLW}$ by 555 kcal/day, with a large range between the lower (~358 kcal/day) and the upper (1,457 kcal/day) limit of agreement (mean bias ± 2 SD). There was an inverse relationship ($r = -0.65$, $P < 0.001$) between TEE bias and the mean of TEE$_{DLW}$ and TEE$_{PAR}$. TEE$_{PAR}$ bias (TEE$_{DLW}$ - TEE$_{PAR}$) was lowest in the pubertal girls (gender by maturation interaction $P = 0.008$; Table 5). As shown in Table 6, estimates of TEE$_{PAR}$ prediction bias were minimized with increasing values of age ($P < 0.001$) and percentage of body fat ($P = 0.007$). The influence of age was dependent on the gender (age × gender: $P = 0.056$).

TEE bias when setting 1 MET equal to the measured BMR. Setting 1 MET equivalent to the measured BMR and then using multiples of the measured BMR to calculate TEE [TEE$_{PAR(1\text{ MET}=\text{BMR})}$] reduced the mean TEE bias to 60 ± 51 kcal/day but did not perform well for the individual child (Fig. 3B). The lower and upper limits of agreement were −723 and 843 kcal/day. The bias was dependent on the mean TEE (Fig. 3). The bias in TEE$_{PAR(1\text{ MET}=\text{BMR})}$ was modestly inversely related to the age of the children, and the full model did not significantly predict the bias (Table 6). As shown in Table 5, TEE$_{PAR(1\text{ MET}=\text{BMR})}$ was greater in the pubertal than in the prepubertal subjects ($P < 0.001$) and in the boys than in the girls ($P = 0.006$). The prediction bias [TEE$_{DLW}$ - TEE$_{PAR(1\text{ MET}=\text{BMR})}$] was greater in the prepubertal girls than in prepubertal boys and pubertal girls (gender by maturation interaction, $P = 0.08$; Table 5).
Validation of a BMR prediction equation. The Food and Agriculture Organization/World Health Organization/United Nations University (FAO/WHO/UNU) BMR prediction equation (46) has been cross-validated and accurately predicts BMR of children and adolescents (13, 14). We found that the FAO/WHO/UNU prediction equation produced a mean BMR prediction bias of 1.0 kcal/day, with a lower and an upper limit of agreement of −285 and 286 kcal/day, respectively (Fig. 4). There was a direct relationship between the bias and mean BMR due to an underprediction in several pubertal boys.

TEE bias when setting 1 MET equal to the predicted BMR. When BMR estimated from the FAO/WHO/UNU prediction equation was used to calculate TEEPAR [TEEPAR(1 MET = estimated BMR)], the mean bias was 53 ± 50 kcal/day (Fig. 3C), with lower and upper limits of −711 and 817 kcal/day. The bias was inversely related to the mean TEE (Fig. 5). TEEPAR(1 MET = estimated BMR) was greater in the pubertal subjects than prepubertal subjects (P < 0.001) and greater in boys than girls (P = 0.004; Table 5). For TEEPAR(1 MET = estimated BMR), the bias was greater (gender by maturation interaction, P = 0.01) in the prepubertal girls than prepubertal boys and pubertal girls (Table 5).

Utility of PAR data beyond BMR and physical activity data for predicting TEE. OLS regression and the extra sum of squares F-test (see Statistics) were used to determine if PAR information added to the prediction of TEE beyond BMR and physical characteristic data. As shown in Table 7, estimates of TEE were predicted with increasing BMR and height and lower body weight. PAR variables (hours spent in sleep and light, moderate, hard, and very hard activities) were then added to the OLS model to determine if the combined information of these five variables reduced the sum of squares error. The combined information of the five PAR variables did not add \( F(5,58), P = 0.15 \) to the prediction of TEE (Table 7).

**DISCUSSION**

Physical activity is prescribed for reducing the adiposity of children and adolescents, but it is unclear whether AEE, total activity time, or activity intensity is most important for altering their body composition or whether normal, free-living AEE and physical activity have measurable influences on the adiposity of normal-weight youth. Also unclear is whether physical activity data such as those obtained from the PAR can be used to accurately estimate the total daily energy expenditure of youth. We used criterion measures to examine 1) the associations among AEE, qualitative aspects of daily physical activity, body composition, and body fat distribution and the influence of pubertal maturation and gender on these relationships and 2) the validity of the 7-day TEEPAR to estimate TEE\(_{\text{DLW}}\). These studies were completed in a group of children.
and adolescents of normal height, weight, growth velocity, and weight for height.

AEE of normal-weight late preadolescent and adolescent boys and girls has not been reported widely and is rather variable between studies. Similar to the present study (Table 1), Craig et al. (8) reported an AEE of 650 kcal/day for 10-yr-old girls (after a 10% adjustment for TEF taken by us). Bratteby et al. (6) reported a much larger AEE (adjusted for TEF) of 1,226 and 975 kcal/day for 15-yr-old boys and girls, respectively. The TEE and BMR data in the present study are similar to those of previous studies of youth (6, 12, 19).

FM was inversely related to AEE (Fig. 1) and time spent in “very hard” activities but not the total activity time or light (sedentary) activity time (Table 3). The robustness of the inverse relationship between AEE and FM was tested in two ways. Partial correlation demonstrated that the relationship remained significant after adjusting for confounding variables (see RESULTS). Second, from forward stepwise regression (Table 4), AEE contributed to the prediction of FM. Others have also reported an inverse relationship between AEE and adiposity (10, 15, 45). AEE is important in the determination of energy balance, since it is more modifiable than BMR or TEF (44). Our results imply that increasing AEE helps limit the accrual of FM of children, but more so in boys than girls (Fig. 1). Girls appear to require a greater AEE to maintain the same FM as boys (Fig. 1), as noted by the greater (P = 0.02) AEE-FM slope of the boys than girls, and girls maintain a greater FM than boys from late childhood through adolescence despite similar amounts of AEE (Table 1). Although our data do not lend a simple explanation for this gender difference, it may be due to differences in circulating sex steroid hormone concentrations that occur during puberty and their effect on the accrual and distribution of body fat (35). As shown in Table 4, increases in FM were best predicted by being more pubertally mature, the female gender, and lesser amounts of AEE. FM was independent of the intensity or the total activity time of recalled physical activities (see RESULTS).

In contrast, Goran et al. (20) found FM to be more inversely related to total activity time than AEE in obese children. Maffeis et al. (27) found that the percentage of body fat was directly related to sedentary activity time in children but, in contrast to Goran et al. and the present study, not related to activity time or AEE. Goran et al. suggest that long bouts of exercise by children promote an active lifestyle and reduce the snacking associated with sedentary activities. However, in adults, high intensity exercise of shorter duration can produce greater reductions in the percentage of fat than exercise bouts of lower intensity and longer duration (7, 41, 42). The conflicting results may be a function of methodological differences. For AEE, Goran et al. used methods similar to the present study, whereas Maffeis et al. (27) estimated AEE from heart rate and BMR, which overestimate TEE of obese children (26). Different tools [recall (present study), questionnaire (20), heart rate (27)] were used to assess the time spent in physical activity. We used a criterion four-compartment body composition model to estimate FM (34). Goran et al. used a dual-energy X-ray absorptiometry model, and Maffeis et al. used skinfold thicknesses. These methods do not agree with the criterion body composition model and do not predict well for the individual child (34), which would affect the relationship between activity and body composition variables. In addition, previous investigations (20, 27) studied children only. We included both children and adolescents in our study. However, analyzing the data by pubertal maturation group produced similar results in the present study in that AEE was a significant predictor of FM in both prepubertal (r = −0.41, P = 0.03) and pubertal (r = −0.34, P = 0.05) groups. Further detailed investigations are necessary to determine the relative importance of the energy cost of activity vs. the exercise duration for modifying FM of children.

Intuitively, AEE would also seem to be a function of FFM. However, we found that FFM was not related to AEE of youth. There were also no group differences in AEE even though the pubertal boys and girls had a greater body weight and FFM than the prepubertal children (Table 1). This would suggest that the pubertal boys and girls participated in less physical activity because the energy cost for activity should be greater given their greater body weight. Goran et al. (20) suggest that the weak relationship between FFM or phys-

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Table 5. BMR, predicted TEE, and prediction bias of the subject groups when multiples of the assumed, measured, and estimated BMR are used to calculate the energy expenditure

<table>
<thead>
<tr>
<th></th>
<th>Prepubertal Boys</th>
<th>Pubertal Boys</th>
<th>Prepubertal Girls</th>
<th>Pubertal Girls</th>
</tr>
</thead>
<tbody>
<tr>
<td>BMR,† kcal·kg⁻¹·h⁻¹</td>
<td>1.52 ± 0.04</td>
<td>1.27 ± 0.03</td>
<td>1.52 ± 0.08</td>
<td>1.13 ± 0.05</td>
</tr>
<tr>
<td>TEE_PAR,† kcal/day</td>
<td>1,452 ± 81.8</td>
<td>2,016 ± 117</td>
<td>1,224 ± 78</td>
<td>2,058 ± 130</td>
</tr>
<tr>
<td>TEE_PAR (1MET-BMR),† kcal/day</td>
<td>2,159 ± 105</td>
<td>2,591 ± 145</td>
<td>1,769 ± 64</td>
<td>2,283 ± 133</td>
</tr>
<tr>
<td>TEE_PAR (1MET-estimated BMR),† kcal/day</td>
<td>2,208 ± 105</td>
<td>2,489 ± 95</td>
<td>1,799 ± 76</td>
<td>2,318 ± 95</td>
</tr>
<tr>
<td>TEE_LWL-TEE_PAR (1MET-BMR),† kcal/day</td>
<td>722 ± 95</td>
<td>539 ± 91</td>
<td>899 ± 75</td>
<td>179 ± 106</td>
</tr>
<tr>
<td>TEE_LWL-TEE_PAR (1MET-estimated BMR),† kcal/day</td>
<td>75 ± 116</td>
<td>37 ± 94</td>
<td>35 ± 53</td>
<td>46 ± 95</td>
</tr>
<tr>
<td>TEE_LWL-TEE_PAR (1MET-estimated BMR),‡ kcal/day</td>
<td>−34 ± 119</td>
<td>66 ± 78</td>
<td>324 ± 90</td>
<td>−81 ± 78</td>
</tr>
</tbody>
</table>

Values are means ± SE. TEE_PAR, TEE by the physical activity recall (PAR) method assuming 1 metabolic equivalent (MET) = 1 kcal·kg⁻¹·h⁻¹; TEE_PAR (1MET-BMR), TEE by the PAR method using multiples of the measured BMR as 1 MET; TEE_PAR (1MET-estimated BMR), TEE by the PAR method using multiples of the estimated BMR as 1 MET. †Significant gender effect. ‡Significant maturation effect.
ical activity and AEE in children is due to the DLW method combining both weight-bearing and non-weight-bearing physical activity, including sedentary activities. In addition, interindividual differences in nonexercise activity thermogenesis such as fidgeting, restlessness, and other types of nonexercise activity (24) may confound the relationships among AEE and FFM, activity intensity, and activity duration.

The relative impact of subcomponents of energy expenditure and time spent in activities of various intensities on the abdominal fat distribution of children may provide useful clinical information. An accumulation of both AVF (30) and ASF (16) has been associated with reduced insulin sensitivity and increased serum lipid concentrations, the antecedents of type 2 diabetes and cardiovascular diseases that occur during childhood and adolescence. Thus it is important to understand the factors associated with the early development of these conditions. Neither AVF nor ASF was inversely related to AEE after adjusting for confounding variables (see RESULTS). The lack of relationship between these energy expenditure and activity variables and abdominal adiposity may be due to the relatively small amount of AVF and ASF in the normal-weight youth studied. Evaluation of children with elevated AVF and ASF may provide better insight into factors associated with increased abdominal adiposity in childhood obesity.

Table 6. Ordinary least squares regression used to predict the bias in TEE as a linear function of age, gender, percentage of body fat, and TEE

<table>
<thead>
<tr>
<th>Prediction Model When Assuming 1 MET = 1 kcal·kg⁻¹·h⁻¹</th>
<th>Prediction Model When Using Multiples of the Measured BMR as 1 MET</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Coefficient</strong></td>
<td><strong>Coefficient</strong></td>
</tr>
<tr>
<td>Intercept, kcal/day</td>
<td>Intercept, kcal/day</td>
</tr>
<tr>
<td>Age, yr</td>
<td>Age, yr</td>
</tr>
<tr>
<td>Gender</td>
<td>Gender</td>
</tr>
<tr>
<td>TEE, kcal/day</td>
<td>TEE, kcal/day</td>
</tr>
<tr>
<td>Fat, %</td>
<td>Fat, %</td>
</tr>
<tr>
<td>Age X Gender</td>
<td>Age X Gender</td>
</tr>
<tr>
<td>Regression*</td>
<td>Regression*</td>
</tr>
<tr>
<td>R²</td>
<td>R²</td>
</tr>
<tr>
<td>0.001</td>
<td>0.02*</td>
</tr>
</tbody>
</table>

Gender data were coded as girls = 0, boys = 1. *R² from bootstrap validation technique.

![Fig. 3. Bias in total energy expenditure (TEE) measured by doubly labeled water (TEEDLW) minus TEE estimated by physical activity recall (TEEPAR) vs. the mean of TEE DLW and TEEPAR.](image)

A: plot when the BMR is assumed to be 1 MET (1 kcal·kg⁻¹·h⁻¹). B: plot when the measured BMR is used to calculate the TEE. C: plot when the estimated BMR is used to calculate the TEE. ●, Prepubertal boys; ○, prepubertal girls; ▲, pubertal boys; ◊, pubertal girls.

![Fig. 4. Bias in BMR measured by calorimetry (BMRcal) minus the BMR estimated by the Food and Agriculture Organization/World Health Organization/United Nations University (FAO/WHO/UNU) equation (BMRFAO) vs. the mean BMR of both methods.](image)

Fig. 3. Bias in total energy expenditure (TEE) measured by doubly labeled water (TEEDLW) minus TEE estimated by physical activity recall (TEEPAR) vs. the mean of TEE DLW and TEEPAR. A: plot when the BMR is assumed to be 1 MET (1 kcal·kg⁻¹·h⁻¹). B: plot when the measured BMR is used to calculate the TEE. C: plot when the estimated BMR is used to calculate the TEE. ●, Prepubertal boys; ○, prepubertal girls; ▲, pubertal boys; ◊, pubertal girls.
An important issue in pediatric weight regulation research is the ability to accurately estimate total free-living energy expenditure in field settings. The PAR has been used to estimate TEE (3, 4, 36, 38) but has not yet been validated in youth against an accurate method such as DLW. The PAR underestimated TEE (Fig. 3) and more so in the prepubertal than pubertal groups (Table 5). However, comparing Table 2 with previous studies (37), this was not a function of the children recalling less physical activity but rather a function of assuming that the resting energy expenditure of a child was similar to the adult value of 1 kcal·kg⁻¹·h⁻¹. As shown in Table 5, the measured BMR was >1 kcal·kg⁻¹·h⁻¹ in all four groups. Thus multiplying by 1 kcal·kg⁻¹·h⁻¹ resulted in a large underestimation of TEEPAR, and this constant should not be used in pediatric research. The prepubertal boys and girls, whose measured BMR was much greater than the assumed constant, had the greatest underestimation in TEE, whereas the pubertal girls, whose measured BMR most closely approached the assumed constant, had the smallest TEE bias. BMR did not approach 1 kcal·kg⁻¹·h⁻¹ until ~16 yr of age (Fig. 2).

Using multiples of the measured BMR to calculate TEE [TEEPAR(1 MET = BMR)], reduced the mean under-prediction bias by 89% (from 555 to 60 kcal/day; Table 5 and Fig. 3). After correction for the metabolic rate, the prepubertal girls had a larger bias than any other group ($P = 0.08$; Table 5), suggesting that they did not recall activities and/or activity intensities as well as the children in the other groups. These results are consistent with previous findings that the validity of PAR improves with age (37), with the caveat that it only occurs in girls, because the prepubertal and pubertal boys had similar prediction errors. The mean prediction errors for the pubertal girls and prepubertal and pubertal boys of 15–46 kcal/day are well within an acceptable range. However, when we used the measured BMR to calculate the energy expenditure, PAR still did not perform well for an individual child (Fig. 3) and had large ±2 SD limits of agreement [784 kcal/day for $\text{TEE}_{\text{PAR}(1 \text{ MET} = \text{BMR})}]$.

Although the mean prediction bias is less when using multiples of the measured BMR, measuring BMR may be a limitation in field settings and population studies where PAR estimates of TEE would seem most beneficial. Thus we determined if TEE prediction bias could also be diminished when a BMR prediction equation is used that might permit more accurate estimates of TEE in the field. Cross-validation of the FAO/WHO/UNU prediction equation (46) produced a mean bias of 1.0 kcal/day with 2 SD limits of agreement of 286 kcal/day (Fig. 4). Similar to the results when the measured BMR was used, the mean bias was acceptable in all groups but the prepubertal girls (Table 5). The mean bias for all subjects was reduced to 52 kcal/day; however, once again, PAR did not estimate TEE well for an individual boy or girl (Fig. 3).

After accounting for the percentage of body fat, age, and gender, TEE bias when assuming 1 MET = 1 kcal·kg⁻¹·h⁻¹ was no longer related to TEE (Table 6). The inverse relationship between age and TEE bias is likely a result of BMR approaching the assumed 1 MET = 1 kcal·kg⁻¹·h⁻¹ in the older children (Fig. 2). The inverse relationship between the percentage of body fat and TEE bias is likely a result of the older girls having the greatest percentage of body fat (Table 1) and a BMR that most closely approximates 1 kcal·kg⁻¹·h⁻¹ (Table 5).

PAR information did not add to the prediction of TEE beyond that provided by BMR, height, and body weight, suggesting that TEE is best predicted from these other variables (Table 7). Although the PAR does not accurately predict TEE for a given boy or girl, it still has utility to provide important qualitative information regarding the frequency, type, and intensity of activity of children that is not provided by DLW. As discussed above, future research must continue to include accurate measures of both physical activity and AEE to tease apart the importance of sedentary activity (27), physical activity (20), and AEE (present study) for modifying adiposity of children.

In summary, AEE, but not total activity time, is inversely related to FM in children and adolescents. This is likely because 1) AEE is the most modifiable component of TEE, 2) energy balance is more a function of AEE than activity time, and 3) despite an increased incidence of obesity, the energy intake of children and adolescents has not changed perceptibly over the past four decades. AEE is not related to FFM in children and adolescents. The lack of relationship with FFM may be a function of the non-weight-bearing physical activity, including fidgeting and other sedentary activities included in AEE. The underestimation of TEE by PAR in youth is due to the assumption that 1 MET for a child is equal to 1 kcal·kg⁻¹·h⁻¹, when the actual 1 MET value for a child may be as great as 2.
kcal·kg⁻¹·h⁻¹. Assigning an individualized 1 MET value equal to the measured or predicted BMR reduces the mean bias of prepubertal and pubertal boys and pubertal girls to an acceptable level of 15–81 kcal/day or an error of 0.7–3.6%. Prepubertal girls continue to have a large mean underprediction bias of ~350 kcal/day, suggesting that they do not adequately recall their physical activity and/or do not accurately recall the duration or intensity of their physical activity. However, even after utilizing the measured or estimated BMR to calculate TEE, PAR still did not perform well on a child-by-child basis, and large limits of agreement remain. Thus PAR should not be used to determine TEE of children and adolescents in a research setting but may have utility in large population-based studies if an appropriate MET value is used to convert PAR to TEE data. The FAO/WHO/UNU prediction equation appears to offer BMR data that are accurate enough to meet this criterion. Accurate methods for estimating energy expenditure need to be developed for children and adolescents.

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