Predicting total energy expenditure from self-reported dietary records and physical characteristics in adult and elderly men and women¹²

James L Seale

ABSTRACT
Background: Energy requirements and nutrient intakes are commonly estimated from self-reported dietary records, but such estimation has proven to be unreliable. When energy intakes determined from dietary records are compared with energy expenditures measured with the use of doubly labeled water, the former consistently underestimate energy requirements and have a high degree of variability.

Objective: The objective of this study was to reduce the bias and variability of self-reported dietary records through the use of stepwise multiple regression analysis to develop models that relate energy expenditure measured with the use of doubly labeled water to energy intake from dietary records, sex, and fat-free mass (or weight and height).

Design: Data from 54 healthy adult men and women were used to develop these models.

Results: Fat-free mass, energy intake, and sex accounted for 86% of the variability in energy expenditure, whereas energy intake, sex, height, and weight accounted for 83%. When the model relating fat-free mass, energy intake, and sex to energy expenditure was tested on published data, it reduced the bias and variability of self-reported dietary records from −17 ± 27% to 3 ± 16%. When the model relating energy intake, sex, weight, and height to energy expenditure was tested on published data, it reduced the bias and variability of self-reported dietary records from −19 ± 25% to −0.3 ± 19%.

Conclusion: Results from this study indicate that a simple relation can be used to correct self-reported dietary records to estimated energy requirements. Am J Clin Nutr 2002;76:529–34.

KEY WORDS Energy requirement, food intake, energy expenditure, doubly labeled water, dietary records, self-reporting bias

INTRODUCTION

The energy needs of a weight-stable adult population are most appropriately defined from measurements of habitual energy expenditure (EE) (1). Because measurements of habitual EE are often difficult to obtain, energy requirements are frequently determined from estimates of energy intakes (EIs). When the body weight and composition of healthy individuals are stable and the individuals are not growing, pregnant, or lactating, EE and EI are equivalent (1).

Energy requirements can be directly assessed from total energy expenditure (TEE) measured with the use of doubly labeled water (²H,¹⁸O) (2). Naturally occurring, nonradioactive stable isotopes of hydrogen (²H) and oxygen (¹⁸O) are used to label the total body water pool.¹⁸O is eliminated from the water pool as water and carbon dioxide, whereas ²H is eliminated only as water. The difference in the elimination rates of ¹⁸O (kO) and ²H (kH) is related to the carbon dioxide production rate (rCO₂), from which EE can be determined (3).

When energy requirements are estimated from EI, all food consumed must be accounted for during a period when body weight and composition are in a steady state. EI determined from self-reported dietary intake records requires that subjects record the type and amount of all the food that they consume during the assessment period. The EI and nutrient intakes of the entire diet are computed as the sum of the energy and nutrients available from each food item consumed.

Self-reported dietary intake records have played a central role in assessing the nutrient and energy requirements of populations. When EIs estimated from self-reported dietary records are compared with TEE measured with the use of doubly labeled water, the former consistently underestimate energy requirements (4–19). Not only are self-reported dietary records biased; they also have a high degree of variation (18). Trends in the amount of underestimation and variability of self-reported dietary records have been associated with weight, obesity, sex, income, level of education, and living arrangements (16–19).

The purpose of this study was to develop mathematical expressions that relate an individual’s EI and physical characteristics to TEE. The physical characteristics of age, sex, fat-free mass (FFM), and fat mass (FM) were considered in one expression. Because these measurements are not always or readily available, a second expression was developed that included the more easily obtained physical characteristics of sex, age, weight, and height.

SUBJECTS AND METHODS

Subjects

Data from healthy adult women (n = 27) and men (n = 27) aged 32–82 y who participated in studies at the Beltsville Human Nutrition Research Center, Agricultural Research Service, US Department of Agriculture, Beltsville, MD.

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Nutrition Research Center were used to develop mathematical expressions relating TEE measured with the use of doubly labeled water to EI determined from self-reported dietary records. The studies were approved by the Agricultural Research Service Human Studies Review Committee of the US Department of Agriculture and by the institutional review board of Georgetown University, the Penn State Geisinger Institutional Review Board, or the Johns Hopkins Committee on Human Research. All subjects were medically screened and found to be free of metabolic disease. All subjects gave informed consent to participate in this study after the procedures were explained to them. All subjects were financially compensated for their participation.

Dietary intake records

EI was estimated from self-reported dietary intake records collected during 3–7 d. Subjects were required to record the type and amount of all food consumed during a weight-stable period. Subjects were trained by registered dietitians to use scales, measuring spoons, and cups to estimate portion sizes when they were unable to actually measure the food consumed. The dietary records were periodically reviewed in the presence of the subjects to resolve any uncertainty in the entries and to assess the completeness of the record. Subjects were instructed not to change their behavior, including physical activities and eating habits, during the recording period. The completed dietary records were evaluated for energy and nutrient content. The energy content of the entire diet was computed as the sum of the energy available in each food item consumed.

Doubly labeled water

Average daily rCO₂ and EE were determined by using doubly labeled water for 10–14 d. Volunteers were given an oral dose of doubly labeled water (0.14 g H₂¹⁸O/kg body wt and 0.70 g H₂O/kg body wt) after a baseline urine sample was collected. Subjects were given labeled containers and instructions for collecting urine specimens. Second-void urine samples were collected on the first 3 d and last 3 d of the sampling period. Baseline urine samples collected before the dose and second-void urine samples collected on the first 3 d and the last 3 d were analyzed for ²H and ¹⁸O concentrations.

The ²H concentration was determined by using an infrared spectrophotometer (MIRAN 1A-FF; Foxboro/Wilks Inc, South Norwalk, CT) on duplicate vacuum sublimations of urine (20). The CV for repeated values from multiple deuterium analysis of body water samples is 1.57% (PROC GLM; SAS Institute Inc, Cary, NC). The ²H dose was calculated to provide the best accuracy for the given instrument sensitivity for determining ²H₂O clearance for 10–14 d (21). The ¹⁸O concentration was determined in a commercial laboratory with the use of the carbon dioxide equilibrium method and an isotope-ratio mass spectrometer. Blind standards derived from a serial dilution of the H₂¹⁸O dose were included with the samples to validate the laboratory results. Linear regression on the standard concentration versus analyzed values (r² = 0.99999; slope = 0.995 ± 0.001; intercept = 0.000 ± 0.000) indicated accurate ¹⁸O analysis.

The ²H and ¹⁸O zero-time intercepts and elimination rates (kH and kO) were calculated by using least-squares linear regression on the natural logarithm of isotope concentration as a function of elapsed time from dose administration (Corel Quatro Pro 8; Corel Corporation, Ottawa, Canada). The zero-time intercepts were used to determine the isotope pool sizes at the time of dose (21). The ¹⁸O pool size was used to estimate total body water, N (¹⁸O pool size/1.01). rCO₂ was calculated from kH, kO, and N according to equation 1 (22)

\[ r\text{CO}_2 (L/d) = (N/2f_i)(0.10kO - 1.04kH)(1 - 1.05(f_i - f_j)) \] (1)

where the constant isotope fractionation factors (f) are 0.941 (fH), 0.992 (fO), and 1.039 (fO). The respiratory quotients determined from the self-reported dietary records were used to estimate EE from rCO₂. These analytic techniques and computational methods were validated in 9 subjects as having an accuracy of 1.6 ± 2.6% (23).

Body composition

FFM was determined by the isotope dilution of ¹⁸O (FFM = ¹⁸O pool size · 1.01⁻¹ · 0.723⁻¹). FM was determined as the difference between total body weight and FFM.

Statistical analysis

An analysis of variance was used to determine significant differences in physical characteristics, EI, and TEE between the women (PROC GLM; SAS Institute Inc). Multiple regression analysis and stepwise regression analysis were used to develop empirical models that related TEE measured with the use of doubly labeled water to sex, age, FFM, FM, and EI from self-reported dietary records (model 1) and to sex, age, weight, height, and EI from self-reported dietary records (model 2) (PROC GLM, SAS INSIGHT, and PROC REG; SAS Institute Inc). Pitman’s test was used to compare the EE predicted by using model 1 (PEE1) with that predicted by using model 2 (PEE2) (24). The correlation between the sum of the residuals [(PEE1 – TEE) + (PEE2 – TEE)] and the difference in the residuals [(PEE1 – TEE) – (PEE2 – TEE)] was tested (PROC CORR, SAS Institute Inc). Residuals were also tested by using analysis of variance to determine significant differences by sex and age and between normal-weight (BMI < 25; n = 17), overweight (25 < BMI < 30; n = 28), and obese (BMI > 30; n = 9) groups (PROC GLM; SAS Institute Inc).

RESULTS

The physical characteristics, EI, and TEE of the subjects are shown in Table 1. Values in the table represent the mean (±SD)

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**Table 1**

| Physical characteristics, energy intake (EI) from self-reported dietary records, and total energy expenditure (TEE) measured with the use of doubly labeled water of the subjects |
|---|---|---|
| Women (n = 27) | Men (n = 27) |
| Age (y) | 62.1 ± 11.9 (41–80) | 61.2 ± 15.3 (32–82) |
| Height (m) | 1.63 ± 0.06 (1.54–1.73) | 1.76 ± 0.08 (1.60–1.97) |
| Weight (kg) | 68.1 ± 10.0 (52.9–92.7) | 83.9 ± 9.3 (63.3–104.9) |
| BMI (kg/m²) | 25.8 ± 3.8 (17.9–31.7) | 27.2 ± 2.4 (23.1–33.2) |
| FM (kg) | 26.2 ± 8.4 (13.9–44.3) | 23.1 ± 5.6 (8.9–39.1) |
| FFM (kg) | 41.9 ± 2.8 (37.2–48.6) | 60.7 ± 7.4 (48.1–76.4) |
| EI (MJ/d) | 7.49 ± 5.12 (4.77–12.13) | 9.22 ± 2.15 (4.80–13.16) |
| TEE (MJ/d) | 9.55 ± 0.70 (8.20–10.90) | 12.85 ± 1.47 (9.66–15.90) |
| TEE – EI (MJ/d) | 2.07 ± 1.51b | 3.64 ± 1.62b |

**Notes:**
1. × ± SD; range in parentheses. FM, fat mass; FFM, fat-free mass.
2. Significantly different from women, P < 0.05.
3. Determined by isotope dilution (H₂¹⁸O).
4. Determined from self-reported dietary records.
5. Determined by using the doubly labeled water method.
6. Significantly greater than zero.

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By Quast on 27 July 2018
Results from a stepwise regression analysis of TEE measured with the use of doubly labeled water with FFM (in kg), EI (in MJ/d) from self-reported dietary records, and sex (women = 0 and men = 1) are shown in Table 2. The mathematical relation resulting from the stepwise regression that predicts TEE is shown in equation 2:

$$PEE1\ (MJ/d) = 3.332 + 0.114 \cdot FFM + 0.195 \cdot EI + 0.827 \cdot S$$  \hspace{1cm} (2)$$

where \(S\) is sex. The regression analysis indicates that FFM, EI, and sex contribute 86% of the variability in TEE.

Results from a second stepwise regression analysis of TEE measured with the use of doubly labeled water with the more commonly reported variables of sex (women = 0, men = 1), height \((H; \text{ in } m)\), EI (in MJ/d) from self-reported dietary records, and weight \((W; \text{ in } kg)\) are shown in Table 3. The mathematical relation resulting from the stepwise regression that predicts TEE is shown in equation 3:

$$PEE2\ (MJ/d) = -2.158 + 1.839 \cdot S + 5.076 \cdot H + 0.249 \cdot EI + 0.0234 \cdot W$$  \hspace{1cm} (3)$$

The regression analysis indicates that sex, height, EI, and weight contribute 83% of the variability in TEE.

The mean values for PEE1, PEE2, PEE1 – TEE (0.0 ± 6.6% and 0.0 ± 6.9% for the women and the men, respectively), and PEE2 – TEE (0.0 ± 7.3% and 0.0 ± 7.5% for the women and the men, respectively) are shown in Table 4. Individual differences between predicted and measured EE are shown in Figures 1 (PEE1 – TEE) and 2 (PEE2 – TEE). Because sex was a factor in the predictive equations, there was no significant difference between the 2 residuals in the women or the men. There was also no significant difference in residuals between the normal-weight, overweight, and obese groups. Correlation analysis of [(PEE1 – TEE) + (PEE2 – TEE)] with [(PEE1 – TEE) – (PEE2 – TEE)] indicated that the sum of the residuals and the difference between the residuals were not correlated and that the SDs of the residuals were not significantly different.

The mathematical relation for PEE1 (equation 2) was validated with published data for TEE, FFM, EI, and sex (5–8). A summary of the results is shown in Table 5. A comparison of TEE with PEE1 indicated that the mean difference between TEE and PEE1 was 1.4 ± 17% and −6.4 ± 14% in the 39 women and the 11 men, respectively. When TEE was compared with EI directly in the same subjects, the difference was 20.1 ± 29.9% and 6.5 ± 15.1% in the women and the men, respectively. Individual differences between PEE1 and TEE are shown in Figure 3. When the residuals (PEE1 – TEE) were compared by sex and age (≥ or <40 y)
water is an ideal method for estimating energy requirements in a weight-stable adult population. Unfortunately, the practical limitations of cost, the availability of stable isotopes, and the complexity of this method prohibit its use in determining habitual EE outside of a research environment. To a great extent, nutrition researchers and health professionals rely on habitual EE obtained from dietary records, to estimate usual dietary intakes and energy requirements. However, self-reported dietary records consistently underestimate energy requirements (4–16). In the 13 studies cited, EI from self-reported dietary records underestimated TEE measured with the use of doubly labeled water by a combined average of 23% in 253 adults (183 women and 70 men). The degree of underestimation varied from 13% (7) to 50% (13). Because of this bias and variability, the validity of using self-reported dietary records to estimate nutrient and energy intakes is questionable.

The bias and variability associated with the use of self-reported dietary records to estimate EI were shown to be related to several variables, including sex, age, and obesity (15–17). In an attempt to develop a mathematical relation between TEE measured with the use of doubly labeled water and EI from self-reported dietary records, we used stepwise regression with EI, sex, age, FFM, and FM as independent variables. The results of this analysis indicated that FFM, EI, and sex were significant predictors of TEE and contributed 86% of the variability in energy requirements. Because FFM values are not as commonly reported as are height and weight, a mathematical relation was also developed between TEE and EI, sex, age, weight, and height. The results of this analysis indicated that sex, height, EI, and weight were significant predictors of TEE and contributed 83% of the variability in energy requirements. Correlation analysis on the sum of the residuals and the difference between the residuals showed that both expressions predict EE equally well. Both of these mathematical expressions eliminated any significant bias associated with sex or obesity. Age was not a significant factor in either expression. However, because the subject population used to develop these expressions was predominately older (8–40 y) and the age range was somewhat restricted, the application of these results may be limited.

To test the validity of the mathematical expressions developed, both equations were used to predict TEE from published studies in which individual results of TEE, EI, and corresponding physical characteristics were reported. The equation relating TEE to FFM, EI, and sex reduced the bias and variability in reported EI from $-17 \pm 27\%$ to $3 \pm 16\%$ when applied to published data (5–8). Furthermore, the bias in the predicted EE compared with measured EE was not significantly related to sex, age, or obesity. The equation was also developed between TEE and EI, sex, age, weight, and height.

### DISCUSSION

Obesity and the health complications it causes are increasing concerns of the adult population in the United States. Obesity commonly occurs when EI is greater than EE. An accurate estimation of energy requirements is necessary to combat or avoid obesity and its complications. TEE measured with the use of doubly labeled water plotted against mean values for 27 women and 27 men. and between the normal-weight, overweight, and obese groups, no significant differences in the residuals were found.

The mathematical relation for PEE2 (equation 3) was validated with a somewhat larger set of published data for TEE, sex, height, EI, and weight (5, 7–10). A summary of these results is shown in Table 6. A comparison of TEE with PEE1 indicated that the mean difference between TEE and PEE2 was $1.0 \pm 17\%$ and $-0.6 \pm 20\%$ in the 61 women and the 26 men, respectively. When TEE was compared with EI directly in the same subjects, the difference was $20.0 \pm 27.1\%$ and $17.6 \pm 22.0\%$ in the women and the men, respectively. Individual differences between PEE2 and TEE are shown in Figure 4. When the residuals (PEE2 $- \text{TEE}$) were compared by sex and age ($\geq$ or $< 40$ y) and between the normal-weight, overweight, and obese groups, no significant differences in the residuals were found.

### TABLE 5

Results from published data including subjects’ fat-free mass (FFM), energy intake (EI) from self-reported dietary records, total energy expenditure (TEE) measured with the use of doubly labeled water, and energy expenditure predicted from FFM, EI, and sex (women $= 0$ and men $= 1$) (PEE1).

<table>
<thead>
<tr>
<th>Study</th>
<th>Sex</th>
<th>Age</th>
<th>FFM</th>
<th>EI</th>
<th>TEE</th>
<th>PEE1</th>
<th>PEE1 $- \text{TEE}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prentice et al (5)</td>
<td>19</td>
<td>F</td>
<td>32</td>
<td>44.9 $\pm$ 5.7</td>
<td>7.54 $\pm$ 1.56</td>
<td>9.12 $\pm$ 1.69</td>
<td>9.90 $\pm$ 0.73</td>
</tr>
<tr>
<td>Schulz et al (6)</td>
<td>2</td>
<td>F</td>
<td>25</td>
<td>49.0 $\pm$ 2.0</td>
<td>10.50 $\pm$ 1.40</td>
<td>11.05 $\pm$ 0.15</td>
<td>10.94 $\pm$ 0.50</td>
</tr>
<tr>
<td>or $&lt; 40$ y)</td>
<td>4</td>
<td>M</td>
<td>25</td>
<td>62.6 $\pm$ 6.3</td>
<td>14.73 $\pm$ 1.93</td>
<td>14.38 $\pm$ 1.77</td>
<td>14.14 $\pm$ 1.09</td>
</tr>
<tr>
<td>Goran and Poehlman (7)</td>
<td>6</td>
<td>F</td>
<td>64</td>
<td>41.5 $\pm$ 2.7</td>
<td>6.00 $\pm$ 1.57</td>
<td>8.76 $\pm$ 0.88</td>
<td>9.21 $\pm$ 0.33</td>
</tr>
<tr>
<td>or $&lt; 40$ y)</td>
<td>7</td>
<td>M</td>
<td>68</td>
<td>58.3 $\pm$ 4.2</td>
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<td>11.20 $\pm$ 1.53</td>
<td>12.68 $\pm$ 0.57</td>
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<tr>
<td>Clark et al (8)</td>
<td>12</td>
<td>F</td>
<td>39</td>
<td>40.5 $\pm$ 6.6</td>
<td>8.19 $\pm$ 2.74</td>
<td>10.50 $\pm$ 2.10</td>
<td>9.48 $\pm$ 0.77</td>
</tr>
<tr>
<td>or $&lt; 40$ y)</td>
<td>11</td>
<td>M</td>
<td>57</td>
<td>59.9 $\pm$ 5.5</td>
<td>11.55 $\pm$ 2.78</td>
<td>12.35 $\pm$ 2.23</td>
<td>13.21 $\pm$ 1.06</td>
</tr>
</tbody>
</table>

$\overline{x} \pm \text{SD}.$
FIGURE 3. Differences between energy expenditure predicted by using model 1 (PEE1) and total energy expenditure (TEE) measured with the use of doubly labeled water plotted against mean values for 39 women and 11 men who participated in previously published studies (5–8).

FIGURE 4. Differences between energy expenditure predicted by using model 2 (PEE2) and total energy expenditure (TEE) measured with the use of doubly labeled water plotted against mean values for 61 women and 26 men who participated in previously published studies (5–8).

relating TEE to sex, height, EI, and weight reduced the bias and variability in reported EI from $-19 \pm 25\%$ to $-0.3 \pm 19\%$ when applied to published data (5, 7–10). Again, the bias in the predicted EE compared with measured EE was not significantly related to sex, age, or obesity. Although the variability between the subjects in these published studies was higher than that in the population used to develop the equations, the difference between predicted and measured EE in the subjects in the published studies was not significantly different from zero. Both equations appear to reasonably predict average daily EE from EI and measures of physical characteristics.

Physical characteristics such as FFM, sex, age, height, and weight have been related to daily EE measured with the use of doubly labeled water by using regression analysis (25, 26). FFM and age were found to account for 65% of the variability in TEE in 299 adults (25). Weight, height, age, and sex were found to explain 77% of the variability in TEE in 574 individuals (26). EI estimated from self-reported dietary records was added to the variables used to predict daily EE in an attempt to reduce individual variation. While EI contributed modestly in reducing variability in both equations relating TEE to sex, height, EI, and weight, reduced the bias and variability in reported EI from $-19 \pm 25\%$ to $-0.3 \pm 19\%$ when applied to published data (5, 7–10). Again, the bias in the predicted EE compared with measured EE was not significantly related to sex, age, or obesity. Although the variability between the subjects in these published studies was higher than that in the population used to develop the equations, the difference between predicted and measured EE in the subjects in the published studies was not significantly different from zero. Both equations appear to reasonably predict average daily EE from EI and measures of physical characteristics.

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### TABLE 6

Results from published data including subjects’ sex, weight, BMI, energy intake (EI) from self-reported dietary records, total energy expenditure (TEE) measured with the use of doubly labeled water, and energy expenditure predicted from sex, weight, BMI, and EI (PEE2)

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<th>Weight</th>
<th>BMI</th>
<th>EI</th>
<th>TEE</th>
<th>PEE1</th>
<th>PEE2</th>
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<td>Prentice et al (5)</td>
<td>19</td>
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<td>32</td>
<td>70.5 ± 18.1</td>
<td>26.5 ± 6.3</td>
<td>7.54 ± 1.56</td>
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<td>9.64 ± 0.68</td>
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<tr>
<td>Livingstone et al (9)</td>
<td>15</td>
<td>F</td>
<td>35</td>
<td>62.4 ± 7.9</td>
<td>24.1 ± 2.9</td>
<td>8.00 ± 1.82</td>
<td>9.93 ± 1.48</td>
<td>9.46 ± 0.61</td>
<td>−0.47 ± 1.25</td>
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<tr>
<td>Goran and Poehlman (7)</td>
<td>6</td>
<td>F</td>
<td>64</td>
<td>65.2 ± 7.1</td>
<td>23.8 ± 2.7</td>
<td>6.00 ± 1.57</td>
<td>8.76 ± 0.88</td>
<td>9.27 ± 0.40</td>
<td>0.51 ± 0.85</td>
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<tr>
<td>7 M 68 77.1 ± 6.9 25.3 ± 2.3 9.73 ± 0.97 11.20 ± 1.53 12.82 ± 0.61 1.62 ± 1.62</td>
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<td>Clark et al (8)</td>
<td>12</td>
<td>F</td>
<td>39</td>
<td>55.4 ± 7.8</td>
<td>20.7 ± 2.8</td>
<td>8.19 ± 2.74</td>
<td>10.50 ± 2.10</td>
<td>9.48 ± 0.80</td>
<td>−1.02 ± 2.47</td>
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<td>73</td>
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<td>0.03 ± 1.07</td>
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<td>3 M 73 74.0 ± 10.7 23.5 ± 2.3 10.45 ± 1.35 10.79 ± 1.67 13.04 ± 0.63 2.25 ± 1.19</td>
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<tr>
<td>Combined</td>
<td>61</td>
<td>F</td>
<td>43</td>
<td>64.3 ± 13.0</td>
<td>24.3 ± 4.7</td>
<td>7.70 ± 2.03</td>
<td>9.62 ± 1.70</td>
<td>9.53 ± 0.64</td>
<td>−0.09 ± 1.67</td>
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<td>26 M 46 78.3 ± 10.5 25.3 ± 3.0 10.73 ± 2.10 13.02 ± 2.89 13.15 ± 0.87 0.13 ± 2.58</td>
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$\bar{x} \pm SD$. 

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$\bar{x} \pm 2 SD$.
While self-reported dietary records have shown a bias to underreport normal daily EE, they remain an important tool for nutrition researchers and health professionals in determining dietary intake. The bias toward underreporting EE does suggest that many other nutrients contained within the diet may also be underreported and that the degree of underreporting may be related to the bias in EI. Nutrition researchers and health professionals need to consider this error when using these dietary records. The models developed in this study may add some insight into the bias and errors encountered with intake data determined from self-reported dietary records.

Multiple regression analysis relating TEE measured with the use of doubly labeled water to EI from self-reported dietary records, sex, and FFM or height and body weight indicates that most of the variation between subjects was accounted for by using these variables. These results suggest that corrective measures relating EI and variables describing physical characteristics are possible. Although the variability in TEE predicted from the equations developed by using multiple regression analysis may limit the application of these equations to individual energy requirements, application to groups is promising. This possibility deserves further investigation.

REFERENCES


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