Age and sex effects on energy expenditure

Birgite Klausen, Søren Toubro, and Arne Astrup

ABSTRACT The aims of the present study were to examine possible effects of age and sex on energy expenditure independent of differences in body composition, and to develop prediction equations for individual estimation of energy expenditure. The study is based on 235 female and 78 male subjects ranging in age from 15 to 64 y and with body mass indexes (in kg/m²) ranging from 16.9 to 50.5. Basal metabolic rate (BMR), sleeping energy expenditure, and 24-h energy expenditure were measured with standardized protocols by indirect calorimetry in respiratory chambers. Anthropometric data were also recorded. Spontaneous physical activity (SPA) was estimated by a radar system during the chamber stay. About 90% of the variation in 24-h energy expenditure could be explained by differences in fat-free mass, fat mass, SPA, and duration of exercise (SEM: 526 kJ/d), whereas age and sex did not contribute significantly. When comparing energy expenditure adjusted for body composition and activity between two age groups (20–30 y, n = 98 and 50–65 y, n = 39), BMR was 4.6% lower in the older group (P = 0.04) and there was a tendency toward a lower sleeping energy expenditure in the older group (P = 0.06). No sex difference in any energy expenditure measurement could be found after differences in body composition and activity were taken into account. In conclusion, no sex effect and no linear decrease in energy expenditure was found with increased age and the middle-aged subjects had lower BMR than younger subjects independent of body size, body composition and activity. Am J Clin Nutr 1997;65:895–907.

KEY WORDS Energy expenditure, aging, body composition, sex, spontaneous physical activity, fat-free mass, basal metabolic rate, humans

INTRODUCTION Energy expenditure can be divided into two main components: basal metabolic rate (BMR), which is the minimum energy expended in the awake state, and energy expended on physical activity. To this can be added thermogenesis induced by food intake, drugs, exposure to cold, and other stress factors. Chronic imbalance between energy intake and energy expenditure results in either weight gain or weight loss. Most people are capable of keeping a relatively stable weight throughout their adult lives without great effort, but in some parts of the world an increasing number of subjects gain weight and become obese or are obliged to restrain their food intake (1–5). Obesity is commonly associated with hypertension, coronary heart disease, diabetes mellitus, certain cancers, and premature mortality (6).

The amount of energy expended can be related to body composition, which can be divided into two main compartments influencing energy utilization: fat-free mass (FFM), which is the weight of metabolically active tissue, and fat mass, which is the total amount of fat in the body.

Much research has concentrated on why some subgroups are more vulnerable to weight gain than others and many factors have been evaluated, including hormones (7–9), genetics (10–12), body composition (13, 14), body temperature (15), and thermic response to food (16, 17). Two large subgroups with a high prevalence of obesity are middle-aged persons (2–5) and women in general (1, 2). Consequently, several studies have addressed the issue of whether energy expenditure decreases with age and whether females have lower energy expenditure than do males, but the literature is equivocal on this topic. Some studies have reported lower energy expenditure, adjusted for body composition, with age (17–21) whereas others have found no difference (16, 22–24). One study found a significantly lower (5–10%) 24-h energy expenditure (25), and another study (26) found a significantly lower (3%) resting metabolic rate (RMR) in the female population.

Many of the reported studies have the shortcoming of including only a few subjects or having used methods less reliable than energy expenditure measurements in respiratory chambers (26, 27). Over a 5-y period from 1989 to 1994 the energy expenditure of a large number of subjects was measured for ≥ 24 h in the respiratory chambers at our department. For this analysis we selected 313 subjects characterized as healthy, except for some being obese, who had been measured in comparable protocols.

The aim of the present study was to analyze the selected cohort for possible effects of age and sex on three different standardized measurements of energy expenditure: 1) energy expenditure measured between 0100 and 0600, while the subjects were sleeping (EEsleep); 2) energy expenditure measured while subjects were awake but at complete rest after 13 h of fasting (BMR); and 3) energy expenditure measured between 0900 and 0900 the following day (24-h EE).

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TABLE 1
Physical characteristics of 313 healthy subjects measured for 24 h in a respiratory chamber

<table>
<thead>
<tr>
<th></th>
<th>Males (n = 78)</th>
<th>Females (n = 235)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (y)</td>
<td>34.4 ± 11.0</td>
<td>36.4 ± 11.0</td>
</tr>
<tr>
<td>Body weight (kg)</td>
<td>87.6 ± 21.4</td>
<td>72.2 ± 17.6</td>
</tr>
<tr>
<td>Height (cm)</td>
<td>178.2 ± 8.2</td>
<td>166.9 ± 6.0</td>
</tr>
<tr>
<td>BMI (kg/m²)</td>
<td>27.7 ± 7.2</td>
<td>25.9 ± 6.6</td>
</tr>
<tr>
<td>Body fat (kg)</td>
<td>23.5 ± 7.1</td>
<td>25.3 ± 12.7</td>
</tr>
<tr>
<td>Fat-free mass (kg)</td>
<td>64.1 ± 9.4</td>
<td>48.5 ± 6.4</td>
</tr>
<tr>
<td>Body fat (%)</td>
<td>24.7 ± 11.6</td>
<td>30.7 ± 9.3</td>
</tr>
</tbody>
</table>

1 ± SD; range in parentheses.
2,3 Significantly different from males: 2 P < 0.00001, 3 P < 0.0001.

It is possible to measure energy expenditure by indirect calorimetry with a high degree of accuracy and precision (27–32), except for the thermic effect of food (33), and attempts have been made to predict BMR and energy expenditure on an individual basis from given anthropometric and activity measures (5, 28, 31, 34, 35). Another purpose of this analysis was, therefore, to develop new prediction equations for energy expenditure and to assess results published previously.

SUBJECTS AND METHODS

Subjects

Three hundred thirteen adult white subjects (78 males and 235 females) were included in the study. Energy expenditure was measured from March 1989 through July 1994 in a respiratory chamber in accordance with 10 different protocols. Only minor factors differed between the 10 protocols, i.e., the selection of subjects and the proportions of macronutrients in the food. The only important factor that differed was the scheduled activity program, but we were able to adjust for this as described later. These studies were published elsewhere (7, 36–42). The subjects’ characteristics are given in Table 1. Eighty percent of the females were measured in the ovulatory phase and 20% in the luteal phase of the menstrual cycle estimated by questionnaires. Most subjects were recruited through newspapers and some were referred by general practitioners for treatment of obesity. Only healthy individuals with no history of metabolic disorders were included. Written informed consent was obtained from all subjects and all studies were approved by the Municipal Ethical Committee of Copenhagen and Frederiksborg, Denmark.

Energy expenditure

Energy expenditure was measured by indirect whole-body calorimetry on the basis of oxygen uptake, carbon dioxide production, and nitrogen excreted in the urine in a 15-m² respiratory chamber, and was described in detail elsewhere (28, 43). The protocols included standardized measurements of 24-h EE, EEsleep, BMR, spontaneous physical activity (SPA), body composition (FFM and fat mass), and anthropometric measurements.

The volume of the outgoing air from the chamber was measured by the principle of differential pressure (AVA 500; Hartmann & Braun, Frankfurt, Germany). The carbon dioxide concentration of

TABLE 2
Determinants of energy expenditure by single- or multiple-regression analyses

<table>
<thead>
<tr>
<th>Prediction equations</th>
<th>r²</th>
<th>P²</th>
<th>SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>24-hour energy expenditure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>= 2154 + 136.1 FFM</td>
<td>0.81</td>
<td>&lt;0.00001</td>
<td>998</td>
</tr>
<tr>
<td>= 1277 + 132.1 FFM + 193.2 SPA</td>
<td>0.85</td>
<td>&lt;0.00001</td>
<td>621</td>
</tr>
<tr>
<td>= 1490 + 118.8 FFM + 192.1 SPA + 21.1 FM</td>
<td>0.88</td>
<td>&lt;0.00001</td>
<td>565</td>
</tr>
<tr>
<td>= 81.5 + 122.0 FFM + 190.8 SPA + 27.0 FM + 44.1 DE</td>
<td>0.89</td>
<td>&lt;0.00001</td>
<td>526</td>
</tr>
<tr>
<td>= 60.0 + 117.4 FFM + 191.5 SPA + 28.0 FM + 45.0 DE + 144.8 sex</td>
<td>0.90</td>
<td>NS</td>
<td>526</td>
</tr>
<tr>
<td>= 387.8 + 116.2 FFM + 190.5 SPA + 29.2 FM + 41.0 DE + 140.4 sex - 4.48 age</td>
<td>0.90</td>
<td>NS</td>
<td>526</td>
</tr>
</tbody>
</table>

Sleeping energy expenditure

<table>
<thead>
<tr>
<th>Prediction equations</th>
<th>r²</th>
<th>P²</th>
<th>SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>= 36.3 + 4.75 FFM</td>
<td>0.81</td>
<td>&lt;0.00001</td>
<td>24.3</td>
</tr>
<tr>
<td>= 47.3 + 4.05 FFM + 1.12 FM</td>
<td>0.87</td>
<td>&lt;0.00001</td>
<td>20.1</td>
</tr>
<tr>
<td>= 30.6 + 3.98 FFM + 1.11 FM + 3.67 SPA</td>
<td>0.88</td>
<td>&lt;0.00001</td>
<td>19.2</td>
</tr>
<tr>
<td>= 9.78 + 4.02 FFM + 1.19 FM + 3.66 SPA + 0.58 DE</td>
<td>0.89</td>
<td>&lt;0.05</td>
<td>19.1</td>
</tr>
<tr>
<td>= 11.2 + 4.01 FFM + 1.20 FM + 3.65 SPA + 0.57 DE - 0.02 age</td>
<td>0.89</td>
<td>NS</td>
<td>19.1</td>
</tr>
<tr>
<td>= 10.6 + 4.04 FFM + 1.19 FM + 3.65 SPA + 0.56 DE - 0.02 age - 0.75 sex</td>
<td>0.89</td>
<td>NS</td>
<td>19.2</td>
</tr>
</tbody>
</table>

Basal metabolic rate

<table>
<thead>
<tr>
<th>Prediction equations</th>
<th>r²</th>
<th>P²</th>
<th>SEM</th>
</tr>
</thead>
<tbody>
<tr>
<td>= 59.5 + 4.55 FFM</td>
<td>0.80</td>
<td>&lt;0.00001</td>
<td>24.1</td>
</tr>
<tr>
<td>= 110.7 + 4.35 FFM - 1.36 DE</td>
<td>0.81</td>
<td>0.002</td>
<td>23.5</td>
</tr>
<tr>
<td>= 98.4 + 4.30 FFM - 1.33 DE + 2.42 SPA</td>
<td>0.82</td>
<td>&lt;0.04</td>
<td>23.2</td>
</tr>
<tr>
<td>= 96.7 + 4.15 FFM - 1.19 DE + 2.42 SPA + 0.26 FM</td>
<td>0.82</td>
<td>NS</td>
<td>23.1</td>
</tr>
<tr>
<td>= 109.8 + 4.10 FFM - 1.30 DE + 2.37 SPA + 0.32 FM - 0.24 age</td>
<td>0.82</td>
<td>NS</td>
<td>23.1</td>
</tr>
<tr>
<td>= 108.1 + 4.18 FFM - 1.33 DE + 2.36 SPA + 0.30 FM - 0.24 age - 2.56 sex</td>
<td>0.82</td>
<td>NS</td>
<td>23.1</td>
</tr>
</tbody>
</table>

1 This analyses is based only on subjects for whom a spontaneous physical activity (SPA) measurement is available; n = 192 (60 males and 132 females). Predictors are added in order of significance. Energy expenditure values are expressed in kJ; fat-free mass (FFM) and fat mass (FM) in kg; duration of exercise (DE) in min; age in y; SPA, without the contribution from the bicycling sessions, is expressed as a percentage of total time spent in the respiratory chamber (mean values are 5.6% for women and 5.8% for men). For sex, female = 0 and male = 1. The constants in the last three equations of 24-h EE and EE sleep are nonsignificant. Predictors in italic are nonsignificant.

2 Significance for the last predictor added.

3 Sleeping energy expenditure was measured from 0100 to 0600.

4 BMR was measured from 0800 to 0900.
the outgoing air was measured by infrared analysis (Uras 3G; Hartmann & Braun) and the oxygen concentration by the paramagnetic principle (Magnos 4G; Hartmann & Braun). 24-h EE was measured from 0900 to 0900 the following morning and EE_{sleep} was measured between 0100 to 0600, when most subjects were in deep sleep. BMR was measured for 1 h from 0800 to 0900 the second morning after 13 h of fasting, with subjects awake but still lying relaxed in bed.

The scheduled physical activity of the 24-h EE program only differed in the duration of the exercise bout. The exercise was carried out on an ergometer bicycle with 75 W in work output. During the chamber stay the subjects were fed a weight-maintenance diet based on the following equation:

\[ \text{Energy intake (kJ/24h)} = 153.9 \times \text{FFM} + 1166 \]  

The fat energy content varied from 28.9% to 37.0%, carbohydrate energy content from 48.0% to 55.0%, and protein energy content from 15.0% to 18.7%.

SPA was assessed by two microwave radar detectors (Sisor Mini-Radar; Static Input System SA, Lausanne, Switzerland), which continuously emit and receive a signal. When the radar detects a moving object a signal is generated and received by the transceiver. The SPA measurements indicate the percentage of time the subjects are active to a detectable degree. SPA was only measured in a subgroup of 60 males and 132 females. The subjects were kept under 24-h surveillance by a laboratory technician during the day and by medical students during the night. Previously reported within-subject day-to-day CVs in our respiratory

\[ \text{Adjusted 24-h EE} = 2213 + 138.5 \times \text{FFM} \]  

\[ r^2 = 0.85; P < 0.00001 \]  

\[ \text{Adjusted 24-h EE} = 8809 + 28.6 \times \text{FM} \]  

\[ r^2 = 0.37; P < 0.00001 \]
chamber are 9.7% for SPA, 1.5% for 24-h EE, and 1.8% for EE

Body weight was measured on a decimal scale (model 707; Seca, Copenhagen). Body composition was estimated by bio-electrical impedance analysis using an Animer (HTS-Engineering Inc, Odense, Denmark). FFM and fat mass were calculated by using the equation of Heitmann (44).

Statistical analyses

Statistical analyses were performed with SPSS 5.0.1. for Windows (SPSS Inc, Chicago). The relation between energy expenditure of the whole population and its possible determinants (FFM, fat mass, age, sex, duration of exercise, and SPA) was assessed by simple- or multiple-regression analysis ($P < 0.05$). Regression equations are presented with $r^2$ values, $P$ values for the last determinant added, and SEs. Group differences were tested by unpaired $t$ test. Group means are presented with ranges in parentheses. Comparisons of slopes and intercepts of the regression lines between different groups of subjects was accomplished as described elsewhere (45). Adjustments or normalization of the energy expenditure data for comparison between different groups or for graphical purposes were made according to Ravussin and Bogardus (46) by using the following equation:

$$\text{Adjusted EE} = \text{EE}_{\text{measured}} + \text{slope(determinant_mean)} - \text{determinant}_{\text{measured}} \quad (2)$$

Slope is the parameter that derives from the multiple-regression equations made from energy expenditure on its determinants. Determinants of energy expenditure are age, sex, FFM, fat mass, duration of exercise, and SPA.

FIGURE 2. Relations between fat-free mass (FFM) and energy expenditure measured from 0100 to 0600 (EE_{sleep}) adjusted for differences in duration of exercise and spontaneous physical activity (top). The relation between fat mass (FM) and EE_{sleep} adjusted for differences in duration of exercise, spontaneous physical activity, and FFM (bottom). $n = 60$ males and 132 females.
TABLE 3
Comparison of energy expenditure (EE) and activity level in a young (20–29 y) and a middle-aged (50–65 y) group of subjects measured for 24 h in a respiratory chamber

<table>
<thead>
<tr>
<th></th>
<th>Young (n = 98)</th>
<th>Middle-aged (n = 39)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24-h EE (kJ/d)</td>
<td>9521 (6661–13928)</td>
<td>9649 (7195–14681)</td>
</tr>
<tr>
<td>Adjusted 24-h EE (kJ/d)1</td>
<td>9372 (7811–11320)</td>
<td>9365 (8269–10635)</td>
</tr>
<tr>
<td>BMR (kJ/h)2</td>
<td>309 (210–503)</td>
<td>326 (227–412)</td>
</tr>
<tr>
<td>Adjusted BMR (kJ/h)2</td>
<td>323 (261–487)</td>
<td>308 (266–352)</td>
</tr>
<tr>
<td>EE_{sleep} (kJ/h)2</td>
<td>291 (202–454)</td>
<td>310 (217–514)</td>
</tr>
<tr>
<td>Adjusted EE_{sleep} (kJ/h)2</td>
<td>291 (230–357)</td>
<td>283 (250–367)</td>
</tr>
<tr>
<td>Body weight (kg)</td>
<td>73.3 (49.3–146.7)</td>
<td>92.2 (59.1–153.0)</td>
</tr>
<tr>
<td>Fat-free mass (kg)</td>
<td>53.5 (38.6–83.9)</td>
<td>54.9 (41.5–83.5)</td>
</tr>
</tbody>
</table>

1: range in parentheses. BMR, basal metabolic rate; EE_{sleep}, sleeping metabolic rate.
2: Metabolic rates adjusted for the significant predictors: see Table 2. (The mean spontaneous physical activity (SPA) value, which is 5.6% for females and 5.8% for males, is used to adjust the subjects without an SPA measure).
3: BMR was only available for 94 young and 23 middle-aged subjects.
4,5: Significantly different from young group. 4 P = 0.040, 5 P < 0.0001.

RESULTS

Prediction of energy expenditure

The successive addition of the known determinants of energy expenditure to the multiple-regression equations of both sexes is shown in Table 2. In this analysis, only data from the 192 subjects (60 males and 132 females) for whom SPA was available were used. For all measurements of energy expenditure (24-h EE, EE_{sleep} and BMR) the major determinant was FFM, which explained ~80% of the variance. SPA explained another 5% of the variance in 24-h EE. Fat mass and duration of exercise were also significant determinants of 24-h EE. Together, FFM and fat mass and the two measures of activity, SPA and duration of exercise, explained 90% of the variance in 24-h EE. The same four determinants explained 89% of the variance in EE_{sleep} but here, FFM and fat mass were the major determinants and explained 87% of the variation. Fat mass was not a significant determinant of BMR, but FFM, SPA, and duration of exercise together explained 82% of the variance in BMR. Sex and age did not explain further variance in any measurement of energy expenditure when body composition was taken into account.

To illustrate the relative contributions from the major determinants of energy expenditure (FFM and fat mass), 24-h EE and EE_{sleep} were first adjusted for activity level and hereafter for FFM. The graphs of the simple regression of 24-h EE and EE_{sleep} respectively, adjusted for activity (SPA and duration of exercise) versus FFM are shown in Figures 1 and 2 (top). Figures 1 and 2 (bottom) show 24-h EE and EE_{sleep} respectively, adjusted for both activity and FFM versus fat mass.

To test our own prediction equations we took 21 subjects from a later protocol, who were measured in exactly the same way, and compared their estimated energy expenditure with measured energy expenditure. No significant difference was found.

Influence of age

To investigate whether there was any age effect not accounted for by the significant determinants of energy expenditure (duration of energy, SPA, FFM, and fat mass) we compared two extreme age groups: young subjects from 20 to 29 y of age (n = 98) and middle-aged subjects from 50 to 65 y of age (n = 39). SPA values were available for 48 subjects in the young group and 38 subjects in the older group. To test for an independent effect of age we adjusted 24-h EE and EE_{sleep} for differences in duration of exercise, SPA, FFM, and fat mass (adjusted 24-h EE and adjusted EE_{sleep} and BMR for FFM,
duration of exercise, and SPA (adjusted BMR). Adjusted and unadjusted values are shown in Table 3. There were no significant differences between unadjusted values of the two age groups. When adjusted for differences in body composition and activity level, BMR was 4.6% lower in the middle-aged group ($P < 0.05$). A clear tendency in the same direction was seen in EE_{sleep} ($P = 0.06$), but no difference was detected in 24-h EE.

The relation between weight, fat mass, FFM, and FFM adjusted for the weight differences seen with increasing age is shown in Figure 3. From age 15 to 65 y a mean weight difference of $\approx 8$ kg was seen, an increase of $\approx 11$ kg fat mass and a decrease of $\approx 3$ kg FFM. When adjusted for this weight change, a relative decrease of $\approx 5$–6 kg FFM was seen from age 15 to 65 y. In Figures 4 and 5 the corresponding declines in 24-h EE and EE_{sleep} are shown.

Influence of exercise

In Figures 6 and 7 the metabolic rates (24-h EE, \( \text{EE}_{\text{sleep}} \) and BMR) are adjusted for body composition. In Figure 6 they are also adjusted for duration of exercise and in Figure 7 for SPA. Both show that daytime activity is best reflected by the complete 24-h period of energy expenditure measurement, which also gave the highest correlation between activity and energy expenditure, than by energy expenditure measurements taken for a few hours during sleep. EE_{sleep} also rose in relation to increasing activity, but not as much as did 24-h EE. In addition, BMR was positively associated with SPA—with a slight positive slope—but it was inversely correlated with duration of exercise.

Influence of sex

Data on energy expenditure by sex are presented in Table 4. There was no difference between males and females in mean values of SPA and duration of exercise. Unadjusted, the metabolic rates were significantly higher for males, but energy expenditure adjusted for activity (SPA and duration of exercise) and body composition (FFM and fat mass) eliminated the sex differences. The regression equations for each sex are shown in Table 5. Age was not a significant determinant in any case. Duration of exercise was not a significant determinant of EE_{sleep} or BMR, but contributed significantly to the prediction of 24-h EE. Fat mass was not a determinant in males, but it was in females. The sex-specific regression lines between 24-h EE and EE_{sleep} adjusted for activity versus FFM and 24-h EE and EE_{sleep} adjusted for activity and FFM versus fat mass are shown in Figures 8 and 9. There were no significant differences between the sexes with respect to slopes and intercepts.

To minimize the confounding effect of menstrual cycle phase, the subset of subjects older than 49 y (28 females and 11
males) was analyzed with regard to sex effect. There were no significant differences between the two sexes with regard to age, body mass index, or SPA. No significant differences between male and female values for EE_{sleep}, BMR, and 24-h EE were observed.

**Menopause**

Postmenopausal women (aged > 50 y) had a significantly higher energy expenditure than the premenopausal women. No difference remained, however, after adjustment for differences in activity level and body composition.

**DISCUSSION**

The present study of 313 white subjects found that differences in FFM, fat mass, SPA, and duration of exercise could explain most (90%) of the variation in 24-h EE measured in a respiration chamber, leaving a residual variation of only 526 kJ/d. After adjustments for these four covariates, no independent linear effect on the residual variation of age and sex could be found. When comparing the two extreme age groups from the cohort, however, a slightly lower BMR was found among the oldest subjects. The difference was not significant for EE_{sleep} and 24-h EE.

**Effect of age**

Both longitudinal (2) and cross-sectional (47) studies have shown that FFM decreases with age, although there is no evidence that this is a normal physiologic phenomenon. It may conceivably be due to a more sedentary lifestyle during the older years. Consequently, energy expenditure relative to body weight becomes lower with age. The decrease in BMR is estimated to be 1–2% per decade in adult life (3), assuming that body weight remains the same. However, epidemiologic studies have shown that the population gains weight up to 65 y of age (4, 5), causing a compensatory increase in FFM. For every 1 kg body weight gained about one-fourth consists of FFM and three-fourths of fat mass (48, 49). Besides the age-related loss of FFM after 65 y of age, people tend to lose weight in proportions similar to those with which it was gained before age 65 y.

There was no linear age effect on energy expenditure in the total group after differences in body composition and activity were adjusted for. But when we compared BMR adjusted for differences in body composition and activity in two age groups (20–29 y, n = 98, and 50–65 y, n = 39) we found a 4.6% lower BMR in the middle-aged group (P < 0.05). Moreover, there was a similar tendency in EE_{sleep} (P = 0.06). This means that an age-related decrease exists, independent of the energy expenditure decrease caused by the decrease in FFM. The age

![Figure 5](https://academic.oup.com/ajcn/article-abstract/65/4/895/4655508/59x384)
FIGURE 6. Relations between spontaneous physical activity (SPA) and 24-h energy expenditure (24-h EE), sleeping energy expenditure (EE_{sleep}) and basal metabolic rate (BMR) all adjusted for duration of exercise, fat-free mass, and fat mass.

groups chosen were as extreme as possible in the present cohort, but a mean difference of only 30 y was achieved. It is possible that more specific determination of body composition in older people or the inclusion of measurements of energy expenditure in very old people would make the age-specific effect more pronounced. The results observed agree with those in previous studies (17–21) although some studies have not shown an age effect independent of differences in FFM (22–24). One of the latter studies involved a very small number of subjects (13 young and 10 middle-aged males) (22) and none of the studies measured 24-h EE in respiratory chambers, which is considered to be more accurate than measurements of energy expenditure of shorter periods (26, 50).

The age-specific decrease in energy expenditure could be due to a combination of several factors, such as changes in the composition of FFM, the effect of thermogenic hormones, or a down-regulation of metabolism of the mitochondria. The role of thyroid status has been investigated for the age-related decline in energy expenditure (8), but it was found that thyroid function based on circulating hormone concentrations was well preserved up to the eighth decade of life. It is possible, however, that the peripheral action is attenuated. The sympathetic nervous system has also been evaluated. Elderly people have elevated plasma norepinephrine concentrations compared with younger adults but they also have a blunted response to sympathetic activation by isoproterenol infusions, which could explain, in part, the decreased BMR observed in elderly people (51). Diet-induced thermogenesis does not seem to decrease with age (17, 52) and cannot account for the observed decrease in BMR.

The data in Table 3 show a tendency of middle-aged subjects toward a greater unadjusted EE_{sleep} than young subjects, and because evidence suggests that aging is characterized by increased norepinephrine concentrations (51), it could be speculated that middle-aged subjects had more involuntary movements during their sleep. Unfortunately, the number of data sets with SPA measurements is too limited and SPA during sleep is too low to allow a firm conclusion on this issue.

In this cohort, in which the oldest individual was 64 y of age, body weight was higher with greater age, and this finding explains why FFM was not decreasing as a function of age.
(Figure 3), as might be expected. However, FFM adjusted for differences in body weight decreased with age, though not significantly (P = 0.06).

TABLE 4
Energy expenditure (EE) and activity level in 313 healthy subjects measured for 24 h in a respiratory chamber

<table>
<thead>
<tr>
<th></th>
<th>Males (n = 78)</th>
<th>Females (n = 235)</th>
</tr>
</thead>
<tbody>
<tr>
<td>24-h EE (kJ/d)</td>
<td>10 875 (7030–14 185)</td>
<td>8911 (6444–14 681)</td>
</tr>
<tr>
<td>Adjusted 24-h EE (kJ/d)</td>
<td>9427 (7511–11 606)</td>
<td>9390 (7950–11 318)</td>
</tr>
<tr>
<td>BMR (kJ/h)</td>
<td>347 (210–492)</td>
<td>289 (213–503)</td>
</tr>
<tr>
<td>Adjusted BMR (kJ/h)</td>
<td>298 (224–366)</td>
<td>304 (221–483)</td>
</tr>
<tr>
<td>EE_sleeep (kJ/h)</td>
<td>335 (217–465)</td>
<td>274 (198–514)</td>
</tr>
<tr>
<td>Adjusted EE_sleeep (kJ/h)</td>
<td>287 (230–334)</td>
<td>290 (244–367)</td>
</tr>
</tbody>
</table>

1 x; range in parentheses. BMR, basal metabolic rate; EE_sleeep, sleeping metabolic rate.
2 Significantly different from males, P < 0.0001.
3 Metabolic rates adjusted for the significant predictors: see Table 2.
4 The mean spontaneous physical activity (SPA) value is used to adjust the subjects without an SPA measure.
5 BMR was only available for 71 males and 210 females.

As expected, 24-h EE, EE_sleeep, and BMR were positively correlated with SPA (P < 0.00001, 0.00001, and 0.05, respectively). 24-h EE and EE_sleeep also correlated positively with duration of exercise (P < 0.05 and 0.00001, respectively), but BMR was negatively correlated with duration of exercise (P < 0.001).

Effect of sex

Ferraro et al (25) reported previously that 24-h EE was lower in females than in males in a study of 235 white subjects when differences in body composition, age, and activity were adjusted for. The authors did not find a significantly lower BMR or EE_sleeep in females, but they observed a tendency toward a decrease in these measures. However, the females in the study had more body fat than the cohort presented here (39% compared with 30.7% fat) and the males had slightly less body fat than our subjects (22% compared with 24.7% fat), so the prevalence of obesity in the study of Ferraro et al was probably higher in females than in males. An average female and male has 26.9% and 14.7% body fat, respectively (53). It is known, although the literature is equivocal, that in the pre- and post-obese states obesity is related to a low RMR (11, 12). Theoretically, this could mean that the significantly lower energy expenditure in females is the result of increases in BMR and EE_sleeep.
TABLE 5
Determinants of energy expenditure (EE) by multiple regression in each sex separately

<table>
<thead>
<tr>
<th>EE determinant and sex</th>
<th>Prediction equation</th>
<th>$r^2$</th>
<th>SE</th>
</tr>
</thead>
<tbody>
<tr>
<td>24-h EE (kJ/d)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female (n = 132)</td>
<td>$= 818 + 119.7 \text{FFM} + 25.2 \text{FM} + 4009 \text{SPA} + 30.5 \text{DE} - 6.37 \text{age}$</td>
<td>0.84</td>
<td>498</td>
</tr>
<tr>
<td>Male (n = 60)</td>
<td>$= -1034 + 122.2 \text{FFM} + 29.1 \text{FM} + 5783 \text{SPA} + 64.0 \text{DE} + 2.78 \text{age}$</td>
<td>0.87</td>
<td>584</td>
</tr>
<tr>
<td>EE_{deep} (kJ/h)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female (n = 132)</td>
<td>$= 15.1 + 4.19 \text{FFM} + 1.21 \text{FM} + 73.1 \text{SPA} + 0.43 \text{DE} - 0.17 \text{age}$</td>
<td>0.83</td>
<td>18.9</td>
</tr>
<tr>
<td>Male (n = 60)</td>
<td>$= 6.19 + 3.86 \text{FFM} + 1.11 \text{FM} + 131.5 \text{SPA} + 0.20 \text{age} + 0.44 \text{DE}$</td>
<td>0.87</td>
<td>19.9</td>
</tr>
<tr>
<td>BMR (kJ/h)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Female (n = 109)</td>
<td>$= 157.7 + 2.23 \text{FFM} + 1.45 \text{FM} + 65.7 \text{SPA} - 0.33 \text{age} - 0.5 \text{DE}$</td>
<td>0.76</td>
<td>18.2</td>
</tr>
<tr>
<td>Male (n = 53)</td>
<td>$= 33.9 + 5.26 \text{FFM} + 159.0 \text{SPA} - 1.7 \text{DE} - 0.36 \text{age} + 0.08 \text{FM}$</td>
<td>0.85</td>
<td>25.1</td>
</tr>
</tbody>
</table>

$^1$ Predictors are added in order of significance level; predictors in italic are nonsignificant. The constants in the equations, except for the female basal metabolic rates (BMRs) were nonsignificant. Fat-free mass (FFM) and fat mass (FM) are expressed in kg, duration of exercise (DE) in min (mean value is 34.7 min for males and 32.9 min for females), spontaneous physical activity (SPA) as a percentage of total time spent in the respiratory chamber without the bicycling sessions (mean value is 5.6% for females and 5.8% for men).

The methods used in the study of Arciero et al (26) and the present study differ both in the method of estimation of body composition (underwater weighing compared with bioelectrical impedance analysis), in the measurements of energy expenditure found among the females in the study of Ferraro et al was not due to a sex effect, but rather that obese females have a lower energy expenditure per se than their male counterparts in the selected cohort.
AGE AND SEX EFFECTS ON ENERGY EXPENDITURE

FIGURE 9. Relations between fat-free mass (FFM) and energy expenditure measured from 0100 to 0600 (EE_{sleep}) adjusted for spontaneous physical activity and duration of exercise differentiated by sex (top) and between fat mass (FM) and EE_{sleep} adjusted for spontaneous physical activity, duration of exercise, and FFM differentiated by sex (bottom); the two lines are superimposed.

In the luteal phase women might have a higher energy expenditure than in the follicular phase of the menstrual cycle (54, 55). A subset of subjects ≥ 50 y (28 women and 11 males) was therefore used to minimize the confounding effect of menstrual cycle, but no difference could be detected between sexes.

Effect of menopause

In a study based on 407 normal-weight women (18–75 y of age) (5) it was found that FFM decreased significantly after menopause, independent of age and time after menopause. There were 207 premenopausal and 28 postmenopausal women in the present study if postmenopause was defined as age ≥ 50 y. The premenopausal women had a mean of 48.1 kg FFM and 21.6 kg fat mass compared with a mean of 51.2 kg FFM and 37.7 kg fat mass in the postmenopausal women. Both of these differences were significant (P < 0.05).

It is a matter of speculation whether our cohort of subjects is representative of the population in general and whether the results can be generalized. In the present study, most subjects were recruited via newspapers, but this method has the obvious shortcoming of enrolling a majority of persons with a special interest in food and associated items. This could mean that the number of subjects with an energy expenditure differing from the population in general [eg, obese or restrained eaters (11, 56)] is higher than if the subjects were recruited at random.

Prediction equations

Note that in Table 2 most of the variation in energy expenditure is explained by differences in body composition. Even though differences in physical activity were significant, it is important to realize that only a small percentage of the variation can be explained by duration of exercise and SPA.
Our results can be compared with those of two other studies (35, 50). Mifflin et al (35) proposed the following prediction equation for resting energy expenditure (RMR):

\[ \text{RMR (kJ/24 h)} = 42.0 \text{ weight} + 26.3 \text{ height} - 20.7 \text{ age} + 697.2 \text{ sex} - 676.2 (r^2 = 0.71) \]  

which was based on 498 subjects measured in a ventilated hood system for 20 min. Use of the same determinants in our analysis produced the following prediction equations:

\[ \text{BMR (kJ/24 h)} = 45.6 \text{ weight} + 40.8 \text{ height} - 20.4 \text{ age} + 295.2 \text{ sex} - 2409.6 (r^2 = 0.69) \]  

\[ \text{EE}_{\text{sleep}} (kJ/24h) = 49.9 \text{ weight} + 30.2 \text{ height} - 11.0 \text{ age} + 333.1 \text{ sex} - 1665.6 (r^2 = 0.83) \]  

To compare these prediction equations, RMR was calculated by using Mifflin et al’s equation with the present data set. Calculated RMR was compared with measured BMR and measured \( \text{EE}_{\text{sleep}} \) by using a paired \( t \) test. Contrary to expectations, both measured BMR and \( \text{EE}_{\text{sleep}} \) were found to be higher (14% and 8% respectively, \( P < 0.0001 \)) than calculated RMR.

Ravussin and Rising (50) made predictive equations for 24-h EE, BMR, and \( \text{EE}_{\text{sleep}} \) using the same determinants as in our study. Their study was based on 597 healthy subjects (presumably including many Pima Indians) measured in respiratory chambers for 24 h. When we predicted our subjects’ mean energy expenditure from Ravussin and Rising’s equations, the results produced 14%, 15%, and 11% higher values than we measured (\( P < 0.0001 \)). We also compared our measured data with the equations of Schofield et al (57), which are based on a study including 3500 men and 1200 women from different countries and using separate equations for different age groups and sexes, and which use weight as the only predictor. A comparison of the measured BMR in our study with the BMR predicted from the Schofield equations resulted in a measured BMR 10% higher than the predicted BMR.

The difference between the prediction equations found in the literature and those presented here must be methodologic, or due to inaccuracy of the methods used or to the selection of subjects. One example is the different methods of determining body composition. We used the bioelectrical impedance method, Ravussin and Rising measured their subjects by hydrostatic weighing, and Mifflin et al used skinfold thicknesses and circumferences. Mifflin et al did not mention the time of weight measurement or whether it was before or after eating or voiding. Ravussin and Rising (50) did not describe the race of the selected subjects in their study. We conclude, therefore, that it is associated with difficulties in exchanging predictive equations between laboratories.

Although 24-h EE measurements can be made with great precision and accuracy in respiratory chambers, it is more clinically relevant to measure daily energy expenditure by using the doubly labeled water method, because this can be done without restraint of physical activity. 24-h EE measure-ments, however, allow a detailed analysis of the determinants of energy expenditure under control of physical activity, which causes the greatest variability in daily energy expenditure.

In conclusion, we made prediction equations for BMR, \( \text{EE}_{\text{sleep}} \) and 24-h EE, both shared and sex-specific, with predictors that together explained almost 90% of the variation in energy expenditure. We found BMR to be significantly lower in a group of middle-aged subjects than in a young group, which could not be explained by differences in body composition. No effect of sex on any of the measurements of energy expenditure was found. Finally, we found a relative reduction of FFM after menopause.

We are grateful to laboratory technician John Lind for carefully running the respiratory chambers.

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