Effects of age on energy balance ¹⁻³

Susan B Roberts and Gerard E Dallal

ABSTRACT The effects of aging on energy requirements and energy balance have been studied by several research groups using the doubly labeled water method. The weight of evidence from these investigations suggests that current recommended dietary allowances underestimate the usual energy needs of adults of all ages, including older adults. In addition, doubly labeled water studies have found a significant negative association between body fatness and energy expenditure for physical activity, and a significant positive association between energy expenditure for physical activity and fat-free mass. Further studies are needed to refine estimates of energy requirements for different population groups and to address the role of physical activity in the prevention and treatment of obesity. Am J Clin Nutr 1998;68(suppl):975S–9S.

KEY WORDS Energy metabolism, body composition, aging, exercise, fat-free mass, resting energy expenditure, REE, total energy expenditure, TEE, doubly labeled water method

INTRODUCTION

In the past 2 decades there has been a substantial change in our understanding of the effects of aging on energy regulation and energy balance. Early work in the Baltimore Longitudinal Study of Aging (1) documented that, as adults age, energy requirements decrease as a consequence of decreased energy expenditure for physical activity and decreased energy expenditure for resting metabolism.

More recent studies have suggested, however, that this early picture was an oversimplification of a complex issue. Studies highlighting the fact that typical individuals experience an approximate doubling of body fat between 20 and 50–60 y of age and a fall in body fat after 70 y of age (2, 3) led to a number of questions. Why does this pattern of increasing and then decreasing body fat occur? What are the roles of energy intake and energy expenditure in these changes? Are recommended dietary allowances (RDAs) for energy (4, 5) accurate for older adults, especially considering that only one recommendation is given for all adults? (4) provided that age-appropriate fractionation corrections are used (10). The reported precision of doubly labeled water studies in humans is in the range of 3–7% (6, 7), which implies that data can be used both at the group and individual levels. Lesser precision is reported in animal studies (11) but this difference is explained by a several technical issues, including the limited amount of body fluid that can be sampled in many animal species and the necessity of using only a small number of postdose samples to calculate turnover rates.

RDAS FOR ENERGY: ARE THEY ACCURATE FOR OLDER ADULTS?

National recommendations on dietary energy intake have been available since 1941 and are defined as “The energy requirement of an individual is that level of energy intake from food which will balance energy expenditure when the individual has a body size and composition, and level of physical activity, consistent with long-term good health; and which will allow for the maintenance of economically necessary and socially desirable physical activity” (4). According to this definition, RDAs for energy will ideally take into account the healthy range for body weight as well as the levels of physical activity associated with long-term health. Current RDAs (4) suggest that older individuals have a mean TEE, and hence energy requirement, of 1.51 multiples of the resting energy expenditure (REE), which is equal to 9.6 MJ/d (2300 kcal/d) for older men and 7.9 MJ/d (1900 kcal/d) for older women. The ratio of TEE to REE is sometimes referred to as the PAL, or physical activity level.

Our early investigations using the doubly labeled water method to study energy requirements found high mean TEEs in groups of young adults (12), and we subsequently reported a similar finding for both older men and young women (8, 13)—findings consistent with short-term studies of 24-h energy expenditure (14, 15). Although it was not known whether the individual subjects in those studies were representative of the general

¹ From the US Department of Agriculture, Human Nutrition Research Center on Aging at Tufts University, Boston; and the Laboratory of Human Nutrition, Massachusetts Institute of Technology, Cambridge, MA.
² Supported by federal funds from the US Department of Agriculture (contract 53–3K06–5–10) and by NIH grants AG 12829 and DK 46124.
³ Address reprint requests to SB Roberts, Energy Metabolism Laboratory, US Department of Agriculture, Human Nutrition Research Center on Aging at Tufts University, 711 Washington Street, Boston, MA 02111. E-mail: ROBERTS_EM@hnrc.tufts.edu.
population, their self-reported levels of strenuous physical activity were equivalent to amounts assumed in the predictions of energy requirements in the current RDAs. Thus, the hypothesis that current RDAs underestimate usual energy needs was suggested (12). As a potential explanation for why this might be, we noted that the prediction of energy requirements in the RDAs made no allowance for nonpurposeful energy expenditure (eg, fidgeting) (12), which can be substantial in many individuals (16).

After our initial observations in young men (12), most other groups investigating energy requirements noted high mean levels of energy expenditure in older individuals (17, 18), with only one study observing values equivalent to the RDAs (19). The weight of evidence thus suggests that current RDAs may underestimate usual energy needs. A recent compilation of doubly labeled water data from most research groups (20) showed the mean PAL decreasing from 1.67 at 40–64 y of age to 1.62 at 65–74 y of age and to 1.51 at 75 y (Figure 1). Thus, only by 75 y of age does the actual mean for TEE, and hence mean energy requirements, reach the low values suggested in the current RDAs for all individuals.

Although these data are consistent with the hypothesis that current RDAs underestimate usual energy needs, further data are needed to address the potential criticism that individuals who volunteer for doubly labeled water studies of TEE may be unusually active and so mean values may not represent the general population. Research is thus needed on representative population groups with different levels of physical activity. In the meantime, while these data are being collected, the doubly labeled water data currently available arguably represent the best information on which mean energy requirements should be based.

### ENERGY EXPENDITURE FOR PHYSICAL ACTIVITY IN YOUNG AND OLDER ADULTS

Several cross-sectional studies that included older adults observed a negative association between individual TEE-REE ratios and body fat expressed as a percentage of weight (21). Data from our own laboratory illustrate this negative relation (Figure 2), and the characteristics of the population studied are given in Table 1. This approach can be criticized, however, because percentage body fat may be as much a marker of lean body mass (which is the inverse of percentage body fat) as of fat mass. Thus, the negative association seen in some previous studies may be due as much to a positive association of the TEE-REE ratio with fat-free mass as a negative association with body fat.

An alternative to using the TEE-REE ratio in these analyses is to calculate the activity-related energy expenditure by using the following equation:

\[
AEE = 0.9 \times TEE - REE
\]

where AEE is the physical activity-related energy expenditure (MJ/d), and 0.9 is the factor needed to account for the thermic effect of food, which can be assumed to be equal to \( \approx 10\% \) of the TEE.

When partial correlation analysis is used to assess the associations between AEE and both fat-free mass and fat mass, each adjusted for the other along with age and sex and their interactions, a picture emerges comparable with the one in which the TEE-REE ratio is plotted against percentage body fat. The same data set used for Figure 2 (but with one outlier removed, see below), in which partial residuals for AEE are plotted against partial residuals for fat-free mass and fat mass separately, for both young and older adults combined is shown in Figure 3. There is a significant positive association between AEE and fat-free mass, and a significant negative association between AEE and fat mass.

### Table 1

<table>
<thead>
<tr>
<th>Characteristics of subjects in the study</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Young</strong></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Age (y)</td>
</tr>
<tr>
<td>Weight (kg)</td>
</tr>
<tr>
<td>Body fat (% of wt)</td>
</tr>
</tbody>
</table>

1 SEM.
2 n = 9.
and fat mass. The equation relating AEE to fat-free mass and fat mass was the following ($R^2 = 0.556$, $P < 0.001$):

$$AEE = a + 0.109FFM - 0.110Fat$$

where FFM is fat-free mass (in kg), fat is in kg, and $a$ is an age- and sex-specific constant.

Note that a single outlier (an older man with 41 kg fat mass) was removed from these calculations. When included, the statistical significance of fat mass dropped to $P = 0.078$. The subject was identified when a significant quadratic effect in fat mass ($P = 0.021$) was noted that vanished ($P = 0.259$) when the subject was removed from the calculations. His distinctiveness was verified and further shown when least median of squares regression (22, 23) was applied to the data, which set this subject aside and gave results almost identical to those reported above.

**FIGURE 2.** Relation between the ratio of total to resting energy expenditure (TEE:REE) and body fat in young men (○), older men (■), young women (□), and older women (□). $R^2 = 0.260$, $P < 0.001$. Details of the subjects are given in Table 1.

These results and observations suggest that individuals with high fat mass do typically expend less AEE than individuals with the same fat-free mass and less fat mass. However, with the relatively small number of subjects in this analysis it was not possible to analyze the effects in young and older subjects separately. Further research is needed to examine the influence of AEE on body fatness in subjects of different ages.

**AGE AND ENERGY REGULATION**

To examine differences in the ability to accurately regulate energy balance, we conducted a series of overfeeding and underfeeding studies on healthy young and older adult men as described elsewhere (24–29). Details of the men in these studies are summarized in Table 1. Changes in TEE, REE, the thermic effect of feeding (measured over 4 h in response to a test meal containing 25% of estimated energy requirements), and body composition were determined in subjects undergoing experimental overfeeding (4.1 MJ/d more than estimated energy requirements) or underfeeding (3.2 MJ/d less than requirements) during a 3-wk period. In addition, voluntary food intake was measured

**TABLE 2**

<table>
<thead>
<tr>
<th></th>
<th>Younger men</th>
<th>Older men</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Overfeeding</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n = 6$ younger men; 9 older men</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta$Energy intake (MJ/d)</td>
<td>4.00 ± 0.11</td>
<td>4.12 ± 0.08</td>
</tr>
<tr>
<td>$\Delta$Total energy expenditure (MJ/d)</td>
<td>0.08 ± 0.68</td>
<td>0.66 ± 0.44</td>
</tr>
<tr>
<td>$\Delta$Resting energy expenditure (MJ/d)</td>
<td>0.33 ± 0.14</td>
<td>0.10 ± 0.07</td>
</tr>
<tr>
<td>$\Delta$Maintenance energy (MJ/d)$^2$</td>
<td>0.80 ± 0.08</td>
<td>0.38 ± 0.06$^1$</td>
</tr>
<tr>
<td>$\Delta$Weight (g/d)</td>
<td>114 ± 25</td>
<td>108 ± 13</td>
</tr>
<tr>
<td><strong>Underfeeding</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n = 10$ younger men; 9 older men</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\Delta$Energy intake (MJ/d)</td>
<td>$-2.99 ± 0.28$</td>
<td>$-3.36 ± 0.07$</td>
</tr>
<tr>
<td>$\Delta$Total energy expenditure (MJ/d)</td>
<td>$-0.94 ± 0.58$</td>
<td>$-1.03 ± 0.44$</td>
</tr>
<tr>
<td>$\Delta$Resting energy expenditure (MJ/d)</td>
<td>$-0.35 ± 0.05$</td>
<td>$-0.17 ± 0.13$</td>
</tr>
<tr>
<td>$\Delta$Maintenance energy (MJ/d)$^2$</td>
<td>$-0.46 ± 0.09$</td>
<td>$-0.38 ± 0.10$</td>
</tr>
<tr>
<td>$\Delta$Weight (g/d)</td>
<td>$-84 ± 18$</td>
<td>$-99 ± 46$</td>
</tr>
</tbody>
</table>

$^1\bar{x} \pm SEM.

$^2$Resting energy expenditure + the thermic effect of feeding.

$^3$Significantly different from younger men, $P = 0.008$.

These results and observations suggest that individuals with high fat mass do typically expend less AEE than individuals with the same fat-free mass and less fat mass. However, with the relatively small number of subjects in this analysis it was not possible to analyze the effects in young and older subjects separately. Further research is needed to examine the influence of AEE on body fatness in subjects of different ages.

**FIGURE 3.** Relations between partial residuals for physical activity–related energy expenditure (AEE) and partial residuals for fat-free mass (FFM) and fat mass obtained in partial correlation analysis of the young (○) and older (×) men and women, for whom data are summarized in Table 1. Significant relations were observed between AEE and both FFM (partial correlation = 0.590, $P < 0.001$) and fat mass (partial correlation coefficient = $-0.378$, $P < 0.005$).**
during a subsequent 10 d and related to the initial intake required for body weight maintenance. The diet fed during the baseline and experimental periods provided 1.5 g protein/kg body wt; an average of 55% of the nonprotein energy was derived from carbohydrate, and 45% was from fat. Subjects were encouraged to pursue their normal lifestyle and activities, and they kept a record of the duration and types of all sports and other strenuous physical activities performed on each study day.

The values for changes in energy intake and energy expenditure and body weight during overfeeding and underfeeding (note: one young subject was excluded from this analysis because of abnormal REE results) are shown in Table 2. There was no difference between young and older men in changes in body weight, TEE, or REE in response to overfeeding and underfeeding. However, older subjects had consistently smaller REE responses, with the result that the increase in REE with overfeeding tended to be smaller in the older group than in the younger group, and the decrease in REE with underfeeding was likewise smaller. In contrast, the change in maintenance energy expenditure, defined as the average of energy expenditure in fasting and fed states (excluding activity) was significantly lower in older than in young adults in response to overfeeding. This decrease in maintenance energy expenditure was significantly associated with decreased fat-free mass in the elderly subjects, suggesting that aging per se was not responsible for decreased maintenance energy expenditure, but rather was a secondary consequence of the loss of muscle mass (28). Another noteworthy issue arising from data in Table 2 is that the increases in maintenance energy expenditure and TEE with overfeeding were very similar whereas the decrease in maintenance energy expenditure with underfeeding was less than one-half of the decrease in TEE. This suggests that overfeeding was not associated with increased AEE, whereas underfeeding was associated with decreased AEE. On the basis of this observation, it can be speculated that the body has a greater capacity to defend itself against negative energy balance than against positive energy balance, but further studies are needed to address this important issue.

To further explore the trends in REE and TEE in response to overfeeding and underfeeding, values for the true change in energy intake (calculated as the difference between energy intake during overfeeding or underfeeding and TEE during weight maintenance, to avoid error due to inaccurate estimation of weight-maintenance energy requirements) were regressed against energy expenditure and body-composition measures. These data are summarized in Figure 4. Note that there was no significant effect of age group on relations between change in energy intake and either body energy content or TEE. There was, however, a significant effect of age group on the relation between the change in energy intake and REE, confirming the trend observed in the group mean data and emphasizing the greater sensitivity of the measurements of change in REE compared with those of change in TEE or change in body energy content. Although the difference in the change in REE between the young and older subjects in this study was relatively small (and would not have been detectable as a difference in weight change during the relatively short period of study), we estimated that it could potentially account for a 0.5–1-kg weight change over the course of a year (27) and supports the suggestion (26) that the elderly are at increased risk of impairments in energy regulation (body weight loss and gain) (30, 31). An important additional point to be highlighted from these results is that doubly labeled water measurements of TEE, although important for many kinds of studies, may fail to detect small changes in components of energy expenditure that can be determined by indirect calorimetry and are quantitatively of sufficient magnitude to have an important long-term effect on energy regulation.

**SUMMARY**

The doubly labeled water method has provided the means to examine the energy requirements of older individuals and associations between body fat and physical activity that were previously difficult to study. In addition, understanding other aspects of energy regulation, such as the control of food intake and thermogenesis, benefit from combining doubly labeled water methodology with classical techniques such as balance studies and indirect calorimetry. Recent studies using doubly labeled water suggest that current RDAs for energy may underestimate...
the energy needs of typical individuals. In addition, cross-sectional doubly labeled water studies in young and older adults suggest a significant negative association between AEE and body fatness. Further studies in this area are needed.

REFERENCES