Energy requirements and aging

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Abstract

Objective: To summarise the literature on energy requirements and aging.
Design: An analysis and review of published data on components of energy expenditure and total energy expenditure (TEE).
Setting: Data on basal metabolic rate (BMR) and TEE were obtained from the US Institute of Medicine of the National Academies database (all available data from studies published before 2001, collected from 20 researchers willing to provide individual subject results).
Subjects: Those individuals from the database who were 20–100 years of age.
Results: TEE and physical activity level (PAL, defined as the ratio of total to resting energy expenditure) declined progressively throughout adult life in both normal weight and overweight men and women. In normal weight individuals (defined as body mass index (BMI) 18.5–25.0 kg m$^{-2}$) TEE fell by $<150$ kcal per decade, and PAL fell from an average of 1.75 in the second decade of life to 1.28 in the ninth decade. Thermic effect of feeding data from other published studies indicated no consistent change associated with aging.
Conclusions: Aging is associated with progressive declines in resting and TEE, which have implications for defining dietary energy requirements at different stages of adult life.

Keywords
Physical activity level
Doubly labelled water method
Total energy expenditure
Energy requirements

Previous use of the factorial method for determination of energy requirements

Background
Previous recommendations on dietary energy needs were based on the ‘factorial method’ of estimating energy expenditure. The factorial method calculates for 24 hour total energy expenditure (TEE) using information on the time devoted to different activities and the energy costs of each activity, and assumes that TEE is equal to energy requirements in weight stable individuals. The advantage of the factorial method is that it allows for theoretical estimation of TEE for defined activity patterns, and thus, mean expected energy requirements for different levels of physical activity can be defined.

However, there are recognised theoretical problems with the factorial method that create uncertainty about the validity of its predictions of energy requirements. One problem is that it is not feasible to measure the energy costs of all activities performed during normal life. Thus, although generalisations about the energy costs of different daily activities are essential, they may introduce substantial error. Even activities that were once thought to be equivalent to basal metabolic rate (BMR), such as sleeping, have now been shown to have unique energy needs that require separate quantification. A further concern is that the act of measuring the energy costs of specific activities may affect the outcome. For example, embarrassment or awareness may change effort level. In addition, the mechanical difficulties associated with performing an activity while wearing unfamiliar equipment may change the energy costs of some activities.

A further concern is that, by definition and design, the factorial method takes into account only those activities that can be specifically accounted for, such as sleeping, walking, household work and occupational activity. However, 24-hour room calorimeter studies have shown that a significant amount of energy is expended in ‘non accountable' activities such as fidgeting, ranging from 100 to 800 kcal day$^{-1}$ between individuals. It has, therefore, been suggested that the factorial method may underestimate usual energy needs, and most assessments of TEE using the doubly labelled water method have found significantly higher measured values for TEE than predicted energy requirements based on the factorial method. In the two direct comparisons of the factorial method with measured TEE, one found that the factorial method underestimated energy needs and one found no difference between the methods. It should be noted that the latter study investigated an elderly population.
population with a mean age of 70 years. Non-accountable activities such as fidgeting are likely to be reduced in such an elderly population, with the result that the factorial method and doubly labelled water derived estimates of energy requirements would be predicted to be more similar than in a young adult population.

Despite these limitations to the factorial method, other approaches available at the time the Food and Agricultural Organization/World Health Organization/United Nations University (FAO/WHO/UNU) 1985 report\(^1\) was being developed were recognised to be even less satisfactory. For example, the reported energy intakes of weight-stable subjects (i.e. those in energy balance) can theoretically be used to predict energy requirements for weight maintenance. However, clinical studies show weight loss in subjects provided with a diet containing the amount of energy required. However, clinical studies show weight loss in subjects provided with a diet containing the amount of metabolisable energy that they reported eating\(^11–13\). In addition, the doubly labelled water method (see below) gives estimates for TEE in free-living subjects that are consistently higher than reported energy intakes in a wide range of subjects. There is also a particular concern that different population groups underreport energy intake to a different extent – for example, underreporting may be increased in those who are overweight or obese\(^14\). Different races (and perhaps nationalities) may also underreport to a different extent\(^15\), presumably because of different sensitivities to psychological issues relating to eating and body weight.

### The doubly labelled water method for assessment of TEE and energy requirements

The doubly labelled water method is a newer technique for measuring TEE. During formulation of the 1985 recommendations on dietary energy needs\(^1\), it was still in the validation phase of its use in human subjects. Since then, it has become a widely used tool for determining TEE in free-living subjects. As described elsewhere\(^16–18\), the basis of the doubly labelled water method, as originally proposed and developed by Lifson in small animals\(^19,20\), is that two isotopes of water (\(^2\)H\(_2\)O and \(^3\)H\(_2\)O) are administered and their disappearance rates from a body fluid such as urine monitored for a period of time optimally equivalent to 1–3 half-lives for isotope disappearance (7–21 days in most human subjects). The disappearance rate of \(^2\)H\(_2\)O reflects water flux, while that of \(^1\)H\(_2\)O reflects water flux plus carbon dioxide production rate (through the rapid equilibration of the body water and bicarbonate pools resulting from the carbonic anhydrase reaction\(^21\)). The difference between the two disappearance rates can, therefore, be used to quantify carbon dioxide production rate, from which TEE can be calculated.

To predict TEE from a measurement of carbon dioxide production, it is necessary to have an estimate of the respiratory quotient (RQ) of the subject during the measurement period. This is because the heat equivalent of carbon dioxide varies with the substrates being oxidised. Short-term measurements of RQ by indirect calorimetry are not appropriate for use with the doubly labelled water technique because RQ varies during the day in association with food consumption. An alternative and more accurate approach is to estimate RQ from information on the subjects’ dietary intake – either their reported macronutrient intakes or normative data from population surveys. (Note: RQ is better known as FQ, or food quotient, when calculated from dietary data.) This approach assumes that the balance of macronutrients is reported accurately even when energy intake is not. Although this assumption may not be entirely correct\(^22\), FQ varies relatively little with quite wide variations in dietary composition. Diets providing 20% and 40% of energy from fat, for example, have a difference of only 0.06 in their FQ. Thus, making assumptions that normative or individual dietary data provides an accurate estimate of FQ will introduce relatively little error into doubly labelled water determinations of TEE. The assumption that individuals consume a diet providing 30% of energy from fat when true fat intake is 20% or 40% would translate into an error in energy expenditures of about only 3%.

Several validations of the doubly labelled water method have been conducted in which doubly labelled water-derived estimates of TEE were compared with measurements of energy expenditure made in a whole-body calorimeter. Although validation studies conducted in whole-body calorimeters do not mimic normal life conditions, they do allow for an exact comparison of doubly labelled water with classic indirect calorimetry, which is considered to be a gold standard measurement of energy expenditure. As summarised elsewhere\(^16,17\), there was a close agreement between the mean carbon dioxide production rates determined by the two methods in the validation studies. The precision of doubly labelled water measurements, as assessed by the variability of individual doubly labelled water measurements from the indirect calorimetry assessments, was 2–5% in the different studies. These validation studies show that the doubly labelled water method can provide an accurate assessment of carbon dioxide production rate and hence TEE in a wide range of healthy human subjects.

One particular advantage of the doubly labelled water method is that it provides a long-term index of TEE. Because 1–3 half-lives of isotope disappearance are needed for isotopic abundances to be measured accurately by mass spectrometry\(^23\), optimal time periods for doubly labelled water measurements of TEE range from 1 to 3 weeks in most groups of human subjects. Thus, in contrast to other techniques such as the factorial method, doubly labelled water can provide energy expenditure estimations over biologically meaningful periods of time that can reduce imprecision through increased study duration. Moreover, because doubly

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labelled water is non-invasive (requiring only that the subject drink the stable isotopes and provide 3+ urine specimens over the study period), usual activity is not affected and measurements can be made in subjects leading their usual daily lives.

One potential criticism of using available doubly labelled water data is that most of the studies did not use randomly selected individuals, and thus the data may not be representative of typical population groups. For this reason, it should be recognised that the collated doubly labelled water data are not necessarily a perfect dataset from which to derive energy requirements. In relation to this concern, it should be noted that the recent study of TEE by Bratteby et al. measured TEE in a representative population sample, and values are consistent with other doubly labelled water data generated from similar groups. Thus, there is currently no evidence suggesting that the doubly labelled water database is not suitable as a basis for extrapolating to dietary energy recommendations, and the very limited available data on representative populations suggests that it is adequate.

A second potential criticism of using doubly labelled water determinations of TEE as a basis for dietary energy requirements is that it is necessary to assume that TEE is relatively unaffected by fluctuations in energy balance – in other words, increased or decreased energy intake by the subjects during TEE measurements did not cause equivalent changes in TEE (in which case the TEE measurements would reflect energy intake in an adapted state that might not be optimal for long-term good health). This assumption is incorrect in the sense that there is certainly some capacity for TEE to increase or decrease spontaneously when energy intake increases or decreases. However, most overfeeding studies show that overeating is also accompanied by substantial weight gain, and likewise reduced energy intake induces weight loss. Thus, although there is some adaptive capacity of TEE to adjust to changes in dietary energy availability, TEE at approximate weight maintenance appears to be a reasonable estimate of adult energy requirements for stable energy balance when weight is in a healthy range.

A third consideration about use of the National Academy of Sciences doubly labelled water database is that it contains no data from subjects in developing countries. There is currently no information on differences in TEE between individuals of different ages in developing countries, and further information on this topic is needed.

A critical mass of doubly labelled water data has now been accumulated on a wide range of age-groups and body sizes, and, therefore, it is possible to define human energy needs based on doubly labelled water estimates of TEE. A total of 802 data points from 122 studies in adults were obtained for analysis by the National Academy of Sciences, and this database is used here to summarise changes in energy expenditure with aging. The analyses presented here do not include data from published doubly labelled water studies that investigated specific disease states and there are no data from developing countries. In addition to TEE data, we discuss information on changes in BMR and thermic effect of food (TEF) with age.

Changes in BMR with age

BMR is one of the largest components of TEE, comprising 50–70% in most adults. Changes in BMR, therefore, have an important impact on TEE. A decline in BMR with adult aging in both men and women has been recognised for decades and is implicit in the Schofield equations for predicting BMR which were adopted with minor modification for use in the original FAO/WHO/UNU predictions of dietary energy needs. BMR has previously been estimated to decline 1–2% per decade based on longitudinal BMR measurements, and presumably this decline is due in part to the usual loss of fat free mass and gain of less metabolically active fat associated with aging. Most studies additionally suggest that BMR adjusted for the change in fat free mass (FFM) is 5% lower in older adults compared to young ones. The reason for this difference between young and older adults is not known, but may be due to an age-associated disproportionate loss of extremely metabolically active organ tissue and/or a decrease in metabolic rate per unit of specific lean tissues. Recent work has suggested that the decline in BMR with age may not be linear, with a breakpoint for more rapid decline apparently occurring around 40 years in men and 50 years in women. In the case of women, this may be due to an accelerated loss of FFM during menopause.

It should be noted that the secular increases in body weight currently occurring in many countries worldwide may impact on changes in BMR with age. For example, individuals who gain substantial amounts of weight as they get older could theoretically experience no decrease in BMR with age or even an increase in BMR with age, associated with gains of FFM and fat mass. The extent to which BMR may increase or decrease with age will presumably depend on the balance between weight gain tending to increase BMR and aging tending to decrease BMR per unit of FFM.

Figure 1 shows a plot of BMR in relation to age using the BMR data available in the National Academy of Sciences doubly labelled water database. Although this database is smaller than the ones used previously to develop the original FAO equations and the update of those equations by Henry, it uses relatively more recent data which was presumably collected with more accurate instrumentation. Between ages 20 and 96 years, the difference in BMR between individuals within the healthy weight range (BMI

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18.5–25.0 kg m$^2$) averaged a 2.0% decrease per decade in women and 2.9% in men. These values are perhaps somewhat higher than the 1–2% reported previously by Keys. Although no conclusive explanation can currently be given for the discrepant results, a suggested explanation is that TEF does not decline with aging per se, but that some studies may have confounded age with factors that decrease TEF independent of aging, such as obesity and/or digestive problems that limit nutrient absorption.

### Changes in TEE with age

There is a recognised decrease in TEE with age, and TEE is lower in elderly adults than young adults. 24-hour sedentary energy expenditure measured in a whole body calorimeter with flexible activity requirements is also lower in elderly subjects compared to young ones, but in whole body calorimeter protocols in which sedentary activity protocols are standardized 24-hour energy expenditure does not differ between young and old adults. These data indicate declines in both intentional and spontaneous physical activity in old age in free-living individuals.

A summary of TEE and physical activity level (PAL) data from the National Academy of Sciences database is given in Figs. 2 and 3. In addition, Table 1 summarises data per decade of life. In normal weight men and women, in whom weight was relatively similar between individuals up to 60 years of age and then decreased moderately after 60 years, TEE fell progressively from 20 years throughout the entire range of ages on whom data is available (up to 96 years). The decline for both men and women averaged 150 kcal per decade between the second and ninth decades. PAL also decreased with increasing age, from an average of 1.75 for men and women in the second decade to 1.28 in the ninth decade (0.07 PAL units per decade). However, the question of whether PAL decreases linearly with age is not currently known. The cross-sectional PAL data shown in Fig. 3 suggests that PAL may be relatively constant between 20 and 40–50 years and then decreases rapidly. However, there are very few subjects in some decade groups, and thus the apparent findings are uncertain.

Figures 2 and 3 and Table 1 also show values for TEE and PAL in overweight men and women. Values for TEE are...
consistently higher in overweight men and women than in normal weight men and women, but PAL values based on measured BMR show a decline with age similar to that of normal weight men and women. PAL values calculated using BMRs predicted from the Schofield equations were low for overweight men and some decades of life had very few subjects. Thus, the extent to which available data was typical vs. atypical for different groups is not known and additional data is needed before changes in TEE and PAL with age and gender can be described accurately.

The decline in PAL with age in both men and women and normal weight and overweight are reported to parallel an increase in body fat mass, though the extent to which the increase in body fat mass with age is a determinant or a cause of the age-related decrease in energy expenditure for physical activity is not known. Although some elderly individuals clearly are able to maintain very high levels of energy expenditure, mean maximal oxygen consumption declines progressively with age in individuals with different occupations. This suggests that at least some parallel changes in fitness, TEE and body composition with age are an inevitable consequence of the aging process, rather than a cumulative consequence of long-

### Table 1 A summary of collected TEE data: TEE and PAL by decade of adult age in normal weight and overweight men and women. Values are means ± SD

<table>
<thead>
<tr>
<th>Weight</th>
<th>TEE</th>
<th>PAL</th>
<th>BMR</th>
</tr>
</thead>
<tbody>
<tr>
<td>70.7 ± 6.0</td>
<td>3047 ± 510</td>
<td>1.75 ± 0.22</td>
<td>1.73 ± 0.27</td>
</tr>
<tr>
<td>71.7 ± 6.8</td>
<td>2964 ± 429</td>
<td>1.78 ± 0.21</td>
<td>1.75 ± 0.24</td>
</tr>
<tr>
<td>70.6 ± 6.7</td>
<td>3048 ± 419</td>
<td>1.84 ± 0.23</td>
<td>1.81 ± 0.23</td>
</tr>
<tr>
<td>73.1 ± 10.8</td>
<td>2513 ± 401</td>
<td>1.60 ± 0.31</td>
<td>1.47 ± 0.27</td>
</tr>
<tr>
<td>67.8 ± 6.1</td>
<td>2397 ± 437</td>
<td>1.61 ± 0.18</td>
<td>1.72 ± 0.24</td>
</tr>
<tr>
<td>70.0 ± 6.7</td>
<td>2407 ± 374</td>
<td>1.62 ± 0.25</td>
<td>1.71 ± 0.25</td>
</tr>
<tr>
<td>67.1 ± 4.0</td>
<td>1700 ± 239</td>
<td>1.17 ± 0.15</td>
<td>1.24 ± 0.20</td>
</tr>
<tr>
<td>65.6 ± 7.3</td>
<td>1935 ± 156</td>
<td>1.38 ± 0.17</td>
<td>1.43 ± 0.10</td>
</tr>
</tbody>
</table>

**Note:**
- TEE = total energy expenditure; PAL = physical activity level; BMR = basal metabolic rate.
- Using measured BMR values.
- Using BMPI predicted using the Schofield equations.

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term inactivity. Further studies are needed to determine the extent to which energy expenditure for physical activity can be maintained in old age in the general population.

**Summary**

Using available TEE data based on studies in developed countries, BMR, TEE and PAL decrease with age in both
normal weight and overweight men and women. Mean PAL values average 1.75 for men and women aged 20–29.9 years, decrease to 1.65 at 60–69.9 years and 1.28 at 90–96.5 years. The values up to 60 years are higher than anticipated based on current estimates of energy needs. There currently appear to be at most small effects of gender and overweight status on the relative change in TEE and PAL with age, but this conclusion is tentative because the data are currently insufficient for many age-groups.

References

13. Roberts SB. Use of the doubly labelled water method for measurement of energy expenditure, total body water, water intake, and metabolizable energy intake in humans and...
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