

Total Energy Expenditure and Energy Requirements in Healthy Elderly Persons

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To investigate energy requirements in healthy elderly subjects, we assessed the association of total energy expenditure (TEE) with resting metabolic rate (RMR), physical activity, body composition, and energy intake in 13 individuals (aged 56 to 78 years, six women and seven men). Free-living TEE was measured using doubly labeled water, RMR was measured by respiratory gas analysis, and energy expenditure of physical activity (EEPA) was derived from the difference between TEE and RMR, assuming the thermic response to feeding contributes 10% of TEE. Fat mass (FM) and fat-free mass (FFM) were obtained from underwater weighing, $\dot{V}O_2\text{max}$ was determined from a bicycle test to exhaustion, energy intake was obtained from a 3-day food diary, and leisure time activity (LTA) was determined by structured interview. TEE was $2,406 \pm 438$ kcal/d (range, 1,856 to 3,200 kcal/d, or 1.25 to 2.11 times RMR) and was related to $\dot{V}O_2\text{max}$ ($r = .79, P = .001$), LTA ($r = .74, P = .004$), FFM ($r = .69, P = .009$), and FM ($r = -.64, P = .018$). The association between TEE and $\dot{V}O_2\text{max}$ persisted after adjustment for FFM (partial $r = .58, P = .036$). EEPA was related to LTA ($r = .83, P < .0001$) and FM ($r = -.58, P = .039$). Energy intake underestimated TEE by $31\% \pm 18\%$ in women and by $12\% \pm 11\%$ in men. Using stepwise regression, TEE was best predicted by $\dot{V}O_2\text{max}$ and LTA (total adjusted $r^2 = .86$). We conclude the following: (1) TEE varies greatly within healthy elderly subjects due to variations in physical activity; (2) $\dot{V}O_2\text{max}$ has an important role in predicting energy requirements in older individuals; and (3) healthy older individuals underreport energy intake.

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THE AGE-RELATED decline in energy intake and resting metabolic rate (RMR) has been well documented in both cross-sectional and longitudinal studies.¹⁻⁷ In addition, physical activity generally declines with age, although this observation is limited to measurements obtained from self-recorded physical activity diaries or motion sensors.^{8,9} However, a recent study did not detect age-related differences in spontaneous physical activity, as measured in a room calorimeter.⁴ The age-related reduction in energy flux is associated with a concomitant increase in adiposity,¹⁰ which is a risk factor for cardiovascular disease,¹¹ and loss of muscle tissue,^{10,12} which may contribute to the age-related decline in functional independence. Taken together, these observations imply that aging is associated with a breakdown in the balance between energy intake and energy expenditure. A growing focus of our laboratory is therefore to identify environmental factors that can maintain and/or reestablish the homeostatic regulation of energy balance in older persons to promote healthy aging.

The aforementioned studies provide useful data on the age-related changes in RMR and body composition. However, the more valuable information resides in knowledge of total energy expenditure (TEE) in elderly persons, measured under free-living conditions with ample opportunity for socially desirable levels of energy intake and expendi-

ture. Information on TEE under these conditions is essential for a precise characterization of daily energy expenditure, in particular, that associated with the energy expenditure of physical activity (EEPA). Furthermore, information on TEE is required because it is generally accepted that recommendations for energy intake should be based on direct measurements of TEE performed under free-living conditions, in favor of using less reliable measures of energy intake.¹³

James et al have defined the energy requirements of the elderly as being approximately 1.51 times basal metabolic rate.¹³ The approach of James et al is to compute daily energy needs based on subjective assessment of the activity pattern of an individual and a factorial-type calculation based on the energy costs of the various activities performed.¹³ However, this approach is still not based on measurements of TEE under free-living conditions, and clearly does not take into account the potential for individual variation. Thus, in the absence of data on TEE in elderly persons, the aims of the present study were to characterize TEE in free-living healthy elderly individuals using doubly labeled water. In addition, the contributions of RMR, body composition, reported energy intake, cardiovascular fitness, and reported physical activity to the individual variation in TEE were examined to identify effective markers for individual variation in TEE.

SUBJECTS AND METHODS

Subjects

Data from 13 older individuals (aged 56 to 78 years, six women and seven men) are presented. Subjects were recruited from newspaper advertisements and radio announcements, and were all retired individuals living in the rural areas surrounding Burlington, VT. All participants were in excellent general health, as defined by (1) no clinical symptoms or signs of heart disease, as assessed by normal resting and exercise stress test electrocardiograms (ECGs); (2) a resting blood pressure less than 140/90; (3) absence of any prescription or over-the-counter medication that could affect cardiovascular function; (4) no family history of diabetes or obesity; (5) weight stability (± 2 kg) by medical history within the past year;

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and (6) absence of any abnormal liver enzyme or lipid values from a routine blood chemistry screening.

The nature, purpose, and possible risks of the study were carefully explained to each subject before obtaining consent to participate. The experimental protocol was approved by the Committee on Human Research for the Medical Sciences of the University of Vermont.

Outline of Protocol

After an overnight fast, the subjects reported to the Clinical Research Center at 7:00 AM to provide baseline urine and blood samples, after which an oral dose of doubly labeled water was administered. Additional samples were collected as described below. Subjects were free to leave the Clinical Research Center and to continue with their usual daily living patterns, and were unaware that TEE was being measured, as they were informed that the oral dose of doubly labeled water and urine collections were for measurement of body composition. During 3 subsequent days, they were asked to keep a diary of food intake. Ten days after the initial oral dose, subjects returned to the Clinical Research Center in the early evening. RMR was measured the following morning after an overnight fast. The second urine void of the morning was collected to mark the end of the doubly labeled water study period. The subjects underwent further testing to obtain measurements of maximal aerobic capacity ($\dot{V}O_{2\max}$) and body composition.

Measurement of TEE

TEE was measured over a 10-day period using the doubly labeled water technique. The protocol was designed in accordance with the technical recommendations for use of the doubly labeled water method in humans.¹⁴ In designing the protocol, a 2-point method was chosen to maximize the noninvasive, free-living nature of the technique. With this approach, subjects were unaware that energy expenditure and physical activity were being measured, thus reducing the possibility of behavioral modification. The validity of this approach is based on the following: (1) the 2-point and multiple-point methods have been shown to compare well in a group of free-living obese subjects,¹⁵ and (2) the 2-point method is theoretically more accurate under conditions where temporal variation in either energy expenditure or water flux is anticipated.¹⁶

After an overnight fast and collection of a single baseline urine and plasma sample (10 mL), a mixed dose of doubly labeled water was orally administered at 0.15 g $H_2^{18}O$ and 0.075 g 2H_2O per kg body mass. The weight of isotope administered was weighed to the nearest mg, and in practice the subjects received approximately 80 to 120 g of doubly labeled water mixed from 10% (atom percent excess) $H_2^{18}O$ (Cambridge Isotope Laboratories, Cambridge, MA) and 99.8% (atom percent excess) 2H_2O (Icon Services, Summit, NJ) in a ratio of 20:1. After oral administration of the isotopes, the vial was rinsed with 50 to 100 mL tap water, which was then also consumed by the subject. A weighed 1:400 dilution of the dose was prepared for each subject at the time of dosing, and samples of the water used for the dilution and the diluted dose were saved and analyzed with each sample set.

An additional plasma sample was obtained 4 hours after isotope administration. The subjects were then instructed to collect and freeze the second-void urine sample the following morning. A final urine sample was collected from the second void during the morning of inpatient status. All samples were stored in sealed vacutainers at $-70^\circ C$ until analysis by isotope ratio mass spectrometry at the Biomedical Mass Spectrometry Facility of the Clinical Research Center at the University of Vermont. Samples were analyzed in triplicate for $H_2^{18}O$ and 2H_2O using the CO_2 equilibration technique,¹⁷ and the off-line zinc reduction method,¹⁸ respec-

tively. All isotope enrichments are expressed using the relative del per mil (‰) scale.

The CO_2 equilibration technique involved dispensing 1.5 mL of sample into a 10-mL vacutainer and filling it with 99.9% pure CO_2 . Equilibration of ^{18}O between water and CO_2 was achieved by overnight shaking at room temperature. The CO_2 was introduced into a VG Sira II isotope ratio mass spectrometer via an automated carousel sample system (VG, Middlewich, Cheshire, UK) and analyzed for the ratio of mass 46:44. Using this method, the average SD for 91 sets of triplicate samples analyzed for $H_2^{18}O$ enrichment (average enrichment, 93.8‰) was $\pm 0.4\%$, and the SD was independent of the enrichment of the sample analyzed ($r = .33$, $P > .05$). Samples of the water used for dilution and the diluted dose were analyzed as standards concurrently with each sample set.

The zinc reduction method was similar to that previously described,¹⁹ and used the quartz reduction vessels described by Wong and Klein²⁰ and a ratio of 3 μL sample (undistilled) with 100 mg zinc (Biogeochemical Laboratories, Bloomington, IN). Reduction was achieved by heating at $500^\circ C$ for 30 minutes in an aluminum block (Biogeochemical Laboratories). The ratio of mass/charge 3 to mass/charge 2 in the hydrogen gas produced was analyzed using a VG Sira II isotope ratio mass spectrometer equipped with a 20-port automated inlet system (VG). Using this method, the average SD for 65 sets of triplicate 2H_2O sample analysis was $\pm 2.8\%$ at a mean sample enrichment of 334.0‰, and the SD was independent of the enrichment of the sample ($r = .24$, $P > .05$). Samples of the water used for dilution and the diluted dose were analyzed as standards, concurrently with each sample set.

Turnover rates and zero-time enrichments of $H_2^{18}O$ and 2H_2O were calculated from the slope and intercept of the semilogarithmic plot of isotope enrichment in urine versus time after dosing. CO_2 production rates were calculated using the following equation:

$$rCO_2(\text{mol/d}) = 0.4554(D_o K_o - D_h K_h), \quad (\text{Eq 1})$$

where D_o and D_h are the individual, zero-time extrapolated dilution spaces of $H_2^{18}O$ and 2H_2O in moles, and K_o and K_h are the turnover rates of $H_2^{18}O$ and 2H_2O in days^{-1} .

Isotope dilution spaces were calculated using the following equation¹⁴:

$$D(\text{mol}) = \frac{WA}{18.02a} \times \frac{(E_{\text{DOSE}} - E_{\text{WATER}})}{(E_{\text{POST}} - E_{\text{PRE}})}, \quad (\text{Eq 2})$$

where D is the isotope dilution space in moles; W is the weight of water used to make the dilution of the dose; A is the weight of dose administered; a is the weight of dose diluted; E_{DOSE} , E_{WATER} , E_{POST} , and E_{PRE} are enrichments in ‰ of the diluted dose, the water used for the dilution, urine at time zero from back-extrapolation, and in urine prior to dose administration, respectively.

Oxygen consumption was derived by dividing the CO_2 production rate by the food quotient, derived on an individual basis from the composition of the diet, using the equations of Black et al.²¹ TEE was calculated using equation no. 12 of Weir.²²

In calculating CO_2 production rates, isotope dilution spaces were obtained from enrichments at time zero, in favor of using the enrichments in plasma 4 hours after dosing. The advantage of using the intercepts is that the same data is essentially used to calculate turnover rates (slope) and dilution space (intercept), and random analytical errors cancel¹⁴ when turnover rate is divided by dilution space in the calculation of CO_2 production rates. In this study, the dilution space of $H_2^{18}O$, calculated from the 4-hour plasma enrichment, was only 2.0% above the zero-time dilution space

(2,041.1 mol v 2,000.2 mol), and use of the former value would have increased TEE by a similar magnitude.

The equation described for calculating CO₂ production is a combination of the multiple-point method²³ and the 2-point method,²⁴ and uses the individual dilution spaces and turnover rates for both isotopes derived from 2 points. The importance of using the individual dilution spaces is highlighted in the present data because the ²H₂O:H₂¹⁸O dilution space ratio was variable (1.0297 to 1.0793; mean, 1.0503 ± 0.0133) and significantly higher than the traditionally assumed value of 1.029 in younger subjects. If a fixed ratio of 1.04:1.01 for the dilution space of ²H₂O:H₂¹⁸O is assumed, the calculated CO₂ production rates and energy expenditure would have increased by 10.5%. There is no current evidence to explain whether the observed variability in the dilution space ratio has any physiological basis or is simply explained by random analytical error. In this data set, the dilution space ratio of ²H₂O:H₂¹⁸O was not significantly related to sex, age, body mass, fat-free mass (FFM), fat mass (FM), or relative body fatness. Similarly, in analyzing doubly labeled water data from studies in obese subjects, Ravussin et al found no association between body fatness and the dilution space ratio of ²H₂O:H₂¹⁸O.²⁵

To convert CO₂ production to energy expenditure, the individual food quotient values obtained from the 3-day intake diary were used, rather than assuming a constant value of 0.85. The food quotient value averaged 0.88, but varied from 0.83 to 0.93 and was not significantly different between men (0.87 ± 0.03) and women (0.89 ± 0.02). Use of the mean food quotient value rather than the individual value would not have changed the calculated daily energy expenditure by more than ±5%.

Measurement of RMR

RMR was measured for 45 minutes in the early morning after an overnight fast by respiratory gas analysis using a ventilated hood system for breath collections, as previously described.² Flow rate was measured by a pneumotachograph (Vertek, Burlington, VT), and oxygen and CO₂ content of expired air were analyzed using a zirconium cell oxygen analyzer (Ametek, Pittsburgh, PA) and an infrared CO₂ analyzer (Ametek), respectively. Energy expenditure was calculated using the Weir equation.²² Duplicate measures of RMR in nine older volunteers (five men, four women; 65.6 ± 4.0 years) in our laboratory showed a coefficient of variation of 4.3% and an intraclass correlation of 0.96.

Derivation of EEPA

EEPA was derived from measurements of TEE and RMR and an estimation of the thermic response to feeding based on previous results from our laboratory.⁵ The equation is based on the following three-compartment model of TEE:

$$\text{TEE} = \text{RMR} + \text{TEM} + \text{EEPA}, \quad (\text{Eq } 3)$$

where TEE is measured with doubly labeled water; RMR is the daily energy cost of the resting metabolic rate; TEM is the thermic response to meals; and EEPA is the energy cost of daily physical activity.

The contribution of RMR to TEE was assumed to be equivalent to that measured upon awakening. Although we have recently shown that RMR at rest during the day is 6% higher compared with measurements performed in the early morning after an overnight stay in the Clinical Research Center,²⁶ this is partially offset by a reduction in metabolic rate during sleep.

The contribution from the thermic response to feeding was estimated at 10% of TEE, (ie, TEM = 0.1 × TEE) based on

previous studies.⁵ Thus, by substitution,

$$\text{TEE} = \text{RMR} + (0.1 \times \text{TEE}) + \text{EEPA} \quad (\text{Eq } 4)$$

and by solving for EEPA,

$$\text{EEPA} = (0.9 \times \text{TEE}) - \text{RMR} \quad (\text{Eq } 5)$$

Measurement of Body Composition

Body fat was estimated from body density as measured by underwater weighing, with simultaneous measurement of residual lung volume by helium dilution, using the Siri equation.²⁷ FFM was estimated as body mass minus FM. Duplicate measures of body composition by underwater weight in nine older volunteers (five men; four women; 65.6 ± 4.0 years) in our laboratory showed a coefficient of variation of 4.1% and an intraclass correlation of 0.91.

Although body composition data was also available from total body water analysis (by assuming that lean body mass is 73% hydrated), the data from densitometry was used for the correlation analysis between energy expenditure, $\dot{V}O_2\text{max}$, and body composition values. We chose to use the densitometry data because TEE and body composition derived from total body water analysis are not strictly independent of one another, as both numbers are derived from the isotope dilution spaces of ²H₂O and H₂¹⁸O. Values for FFM derived by both methods were highly correlated with one another ($r = .99$, $P < .001$), although FFM derived by underwater weight was systematically higher by 2.4% (50.00 ± 9.50 kg by underwater weight, 49.36 ± 9.41 kg by total body water).

Measurement of $\dot{V}O_2\text{max}$

$\dot{V}O_2\text{max}$ was measured in all subjects as previously described.²⁸ Briefly, this test consisted of cycling at 50 rpm at an initial workload of 25 W (women) and 50 W (men) for 3 minutes, followed by a 25-W increase every 2 minutes until exhaustion, or until subjects were unable to maintain 50 rpm. The attainment of $\dot{V}O_2\text{max}$ requires meeting at least two of the following criteria: (1) attainment of age-predicted maximal heart rate, (2) a maximal respiratory exchange ratio greater than 1.0, or (3) no further increase in oxygen consumption, despite an increase in workload. Duplicate measures of $\dot{V}O_2\text{max}$ in nine older volunteers (five men, four women; 65.6 ± 4.0 years) in our laboratory showed a coefficient of variation of 4.3% and an intraclass correlation of 0.90.

Assessment of Dietary Intake

Energy and macronutrient content of the diet intake were estimated from a 3-day, self-administered food diary, which included 2 week days and 1 weekend day, as previously described.² The purpose of administering the 3-day food diary was to compare this method with measurement of TEE using doubly labeled water, and to obtain individual estimates of the dietary food quotient. We have shown that self-recording of energy intake approximates spontaneous energy intake covertly measured in a clinical research environment in compliant volunteers.²⁹

Assessment of Leisure Time Activity

The energy cost of leisure time activities (LTA) during the previous 12-month period was estimated using The Minnesota Leisure Time Physical Activity Questionnaire,^{30,31} as previously described.² This evaluation is a structured interview that assesses the frequency and duration of participation in recreational activities over the previous 12-month period. Each activity is assigned an intensity code (eg, walking for pleasure, 3.5; cross-country skiing, 8.0) that is multiplied by the total estimated minutes in the year

Table 1. Physical Characteristics of 13 Elderly Subjects

Subject	Age (years)	Height (cm)	BM (kg)	FFM (kg)	FM (kg)	VO ₂ max (L/min)
Females						
No. 1	65	169	69.06	44.6	24.5	1.71
No. 2	60	161	61.90	39.0	22.9	1.74
No. 3	66	168	60.78	38.1	22.7	1.31
No. 4	69	165	79.50	45.3	34.3	1.51
No. 5	56	166	58.93	40.6	18.4	1.56
No. 6	70	165	61.24	41.5	19.8	1.33
Males						
No. 1	59	185	80.29	64.4	15.9	2.94
No. 2	65	167	64.16	56.8	7.4	2.94
No. 3	78	171	79.76	55.7	24.1	1.25
No. 4	69	175	73.16	61.3	11.9	3.00
No. 5	65	162	74.15	51.3	22.9	1.86
No. 6	73	187	80.48	56.4	24.1	2.13
No. 7	70	176	87.58	62.5	25.1	2.07
Mean ± SD (group)	67 ± 6	170 ± 8	71.62 ± 9.52	50.6 ± 9.5	21.1 ± 6.7	1.95 ± 0.64
Mean ± SD (females)	64 ± 5	165 ± 3	65.24 ± 7.80	41.5 ± 2.9	23.8 ± 5.6	1.53 ± 0.18
Mean ± SD (males)	68 ± 6	175 ± 9*	77.08 ± 7.42*	58.3 ± 4.6*	18.8 ± 7.1	2.31 ± 0.67*

NOTE. FM and FFM are derived from underwater weighing.

Abbreviation: BM, body mass.

*Significant ($P < .05$) difference between males and females.

spent performing this activity. The cumulative energy cost for LTA over the previous year was averaged and expressed as kcal/d.

Statistics

Mean values, SD, and ranges are presented for all measures and parameters. Differences between men and women were assessed by an independent *t* test. The Pearson product moment correlation was used to derive the level of association between pairs of variables. Stepwise regression analysis was used to determine the relative contribution of selected independent variables to the variation in dependent variables under examination. All statistical and data manipulations were performed on a personal microcomputer using either Lotus 1-2-3 (Lotus Corp, Cambridge, MA) or Starplan (The Futures Group, Washington, DC) software packages.

RESULTS

Description of Subjects

Table 1 presents a summary of some of the physical characteristics of the elderly subjects, who ranged in age from 56 to 78 years. Men and women were similar with respect to age and FM, although, as shown in Table 1, men were significantly heavier than women, due to a significantly greater FFM. Percent body fat (not shown in table form) averaged $29.5\% \pm 8.9\%$ in the group and was significantly higher ($P < .01$) in women ($36.1\% \pm 4.2\%$) than in men ($28.9\% \pm 7.9\%$). VO₂max ranged from 1.25 to 3.00 L/min and was significantly greater in men, although this difference was not apparent when VO₂max was expressed per kg FFM (38.05 ± 10.4 L/min/kg FFM in men, 34.32 ± 4.37 L/min/kg FFM in women; $P > .05$).

Doubly Labeled Water Data

The initial and final enrichments (above natural background), turnover rates, and dilution spaces for both

isotopes are given in Table 2. On day 1, the enrichments of ²H₂O and H₂¹⁸O were 280 and 310 times the level of analytical error, respectively. The enrichments on day 1 were significantly higher in women for both ²H₂O ($885.5\% \pm 71.1\% \text{ v } 697.5\% \pm 54.8\%$; $P < .001$) and H₂¹⁸O ($133.5\% \pm 11.0\% \text{ v } 111.3\% \pm 11.5\%$; $P < .001$), but by day 10 the enrichments of both isotopes were similar in men and women. There was no significant difference in the turnover rates of either ²H₂O or H₂¹⁸O between men and women. Not shown in table form is the fact that isotope dilution spaces at time zero for both ²H₂O and H₂¹⁸O were

Table 2. Group Data From the Doubly Labeled Water Experiment in 13 Healthy Elderly Subjects

Variable	Mean	SD	Range
² H ₂ O: Day 1 (‰)	784.2	114.5	618.7 to 963.6
² H ₂ O: Day 10 (‰)	353.4	60.2	214.9 to 400.2
H ₂ ¹⁸ O: Day 1 (‰)	121.6	15.8	99.0 to 133.7
H ₂ ¹⁸ O: Day 10 (‰)	43.2	7.1	30.4 to 57.6
K _h (days ⁻¹)	-0.0883	0.015	-0.0741 to -0.1179
K _o (days ⁻¹)	-0.1144	0.018	-0.0988 to -0.1459
D _h , time zero (mol)	2,099.4	396.7	1,627.2 to 2,687.8
D _o , time zero (mol)	2,000.2	385.2	1,572.9 to 2,570.0
D _h :D _o	1.050	0.013	1.030 to 1.079
rCO ₂ (mol/d)	19.4	3.3	15.3 to 24.7
FQ diet	0.88	0.027	0.83 to 0.93
TEE (kcal/d)	2,406	438	1,856 to 3,200

NOTE. Enrichments of ²H₂O and H₂¹⁸O on day 1 and day 10 after dosing are on the relative per mil (‰) scale above predosing values. K_h and K_o are the turnover rates of ²H₂O and H₂¹⁸O from a 2-point method between day 1 and day 10. D_h and D_o are the zero-time dilution spaces of ²H₂O and H₂¹⁸O in urine, obtained by back-extrapolation. rCO₂ is carbon dioxide production corrected for fractionation. FQ is the food quotient of the diet obtained from a 3-day diary, and TEE is averaged over the 10-day study period. See Methods for further details.

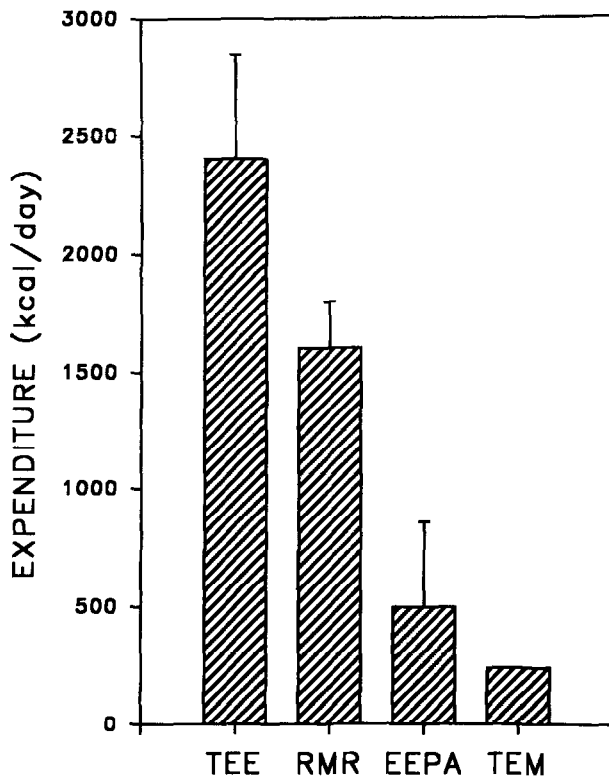


Fig 1. Components of TEE in free-living elderly persons. TEE is measured over 10 days using doubly labeled water; RMR is measured by respiratory gas exchange in the early morning after an overnight stay in the Clinical Research Center; EEPA is derived from TEE and RMR using equation no. 5 (see Methods); TEM is the thermic response to meals, estimated at 10% of TEE based on previous results from our laboratory.⁵

significantly higher in men, although the $D_h:D_o$ ratio was similar in men (1.048 ± 0.012) and women (1.054 ± 0.015).

Components of TEE

A summary of the components of TEE is presented in Fig 1, and the individual raw data for TEE, RMR, EEPA, energy intake, and LTA (questionnaire) are presented in Table 3. TEE and RMR were both significantly higher in men. TEE was equivalent to 1.51 ± 0.27 times RMR (range, 1.25 to 2.11). The RMR contributed $68\% \pm 11\%$ to TEE (range, 54% to 79%), and EEPA contributed $22\% \pm 11\%$ to TEE (range, 10% to 43%).

Interaction Between the Components of TEE and Fitness and Body Composition

A summary of univariate analyses between the dependent variables, TEE, RMR, and EEPA, and the independent physiological parameters under investigation is shown in Table 4. TEE was significantly related to $\dot{V}O_2\max$, LTA from the questionnaire, and FFM, and was inversely related to FM. TEE was not significantly related to age, height, body mass, body mass index, RMR, respiratory exchange ratio, or the food quotient. RMR was strongly related to height, FFM, $\dot{V}O_2\max$, and body mass.

EEPA was significantly related to LTA and inversely related to FM, and there was a trend toward a significant association with $\dot{V}O_2\max$ ($r = .52, P = .069$). EEPA was not significantly related to age, height, body mass, FFM, body mass index, RMR, respiratory exchange ratio, or the food quotient value of the diet.

The correlations between the three components of daily energy expenditure (TEE, RMR, and EEPA) and $\dot{V}O_2\max$

Table 3. Components of Daily Energy Expenditure, Reported Energy Intake, and LTA in 13 Elderly Subjects

Subject	TEE (kcal/d)	RMR (kcal/d)	EEPA (kcal/d)	Intake (kcal/d)	LTA (kcal/d)
Females					
No. 1	1,889	1,454	246	927	154
No. 2	2,001	1,529	272	1,000	191
No. 3	1,856	1,483	187	1,785	224
No. 4	2,101	1,584	307	1,300	61
No. 5	2,238	1,227	787	1,807	470
No. 6	2,467	1,555	665	1,774	126
Males					
No. 1	2,994	1,869	825	2,368	494
No. 2	2,763	1,757	730	1,968	445
No. 3	2,110	1,613	286	2,135	200
No. 4	3,200	1,738	1,142	2,747	628
No. 5	2,895	1,371	1,235	2,448	978
No. 6	2,438	1,930	264	2,225	450
No. 7	2,323	1,728	363	2,388	182
Mean \pm SE (group)	2,406 \pm 438	1,603 \pm 199	562 \pm 358	1,913 \pm 562	354 \pm 256
Mean \pm SD (females)	2,092 \pm 231	1,472 \pm 129	410 \pm 251	1,432 \pm 410	204 \pm 141
Mean \pm SD (males)	2,675 \pm 394*	1,715 \pm 183*	692 \pm 402	2,326 \pm 249*	482 \pm 270*

NOTE. TEE is measured over 10 days with doubly labeled water; RMR is measured by respiratory gas analysis; EEPA is derived from TEE and RMR as described with Equation no. 5 (see Methods); Intake is 3-day reported intake from a diary; LTA is determined over the previous 12 months as estimated by questionnaire.

*A significant difference ($P < .05$) between males and females.

Table 4. Univariate Analysis Between Components of Daily Energy Expenditure and Physiological Variables Under Examination

Parameter	Dependent Variable		
	TEE	RMR	EEPA
Age (yr)	0.1	0.40	-0.29
Height (m)	0.35	0.78*	-0.05
Body mass (kg)	0.25	0.58†	-0.06
FFM (kg)	0.69†	0.75*	0.34
FM (kg)	-0.64†	-0.23	-0.58†
Body mass index (kg/m ²)	0.06	0.05	0.04
RMR (kcal/d)	0.42	—	-0.09
LTA (kcal/d)	0.74*	-0.03	0.83*
$\dot{V}O_2$ max (L/min)	0.79*	0.63†	0.52
RER	-0.47	0.00	-0.48

NOTE. TEE is averaged over 10 days, measured with doubly labeled water; RMR is measured by respiratory gas analysis; EEPA is derived from TEE and RMR as described with Equation no. 5 (see Methods); FFM and FM are derived from underwater weighing; LTA is from the previous 12 months, assessed by questionnaire; $\dot{V}O_2$ max is measured by a test to exhaustion; RER is the fasting respiratory exchange ratio.

* $P < .005$.

† $.005 < P < .05$.

are shown in Fig 2. Since energy expenditure and $\dot{V}O_2$ max are dependent on FFM, the relationship was examined independently of FFM using partial correlation analysis. Thus, when the residuals from the correlation between TEE and FFM were correlated with the residuals from the regression between $\dot{V}O_2$ max and FFM, the partial r value remained significant (partial $r = .58$, $P = .036$; Fig 3). When the same analysis was performed for RMR and EEPA, the partial r values were not significant.

To determine the strongest predictors of TEE in these subjects, data were analyzed using stepwise regression analysis, with TEE as the dependent variable and the unadjusted data for sex, age, height, FM, FFM, LTA (questionnaire), $\dot{V}O_2$ max, RMR, fasting respiratory exchange ratio, 3-day reported food intake, and the food quotient value of the diet as potential independent variables. The first variable selected by the model was $\dot{V}O_2$ max (adjusted $r = .77$), followed by the energy cost of LTA derived from the questionnaire (total adjusted $r = .86$), generating the equation:

$$\text{Tee(kcal/d)} = (391 \times \dot{V}O_2\text{max}) + (0.79 \times \text{LTA}) + 1,363 \quad (\text{Eq 6})$$

where $\dot{V}O_2$ max is expressed as L/min, and LTA (kcal/d) is estimated from a 12-month recall questionnaire. The SE of the estimated TEE predicted from equation no. 6 is ± 217 kcal/d.

Since measurement of $\dot{V}O_2$ max may prove impractical in some elderly populations, a second equation was developed using measurement of RMR in addition to assessment of LTA by questionnaire. Thus, if $\dot{V}O_2$ max is removed from the list of potential independent variables, a second equation with LTA and RMR (total adjusted $r = .83$) was

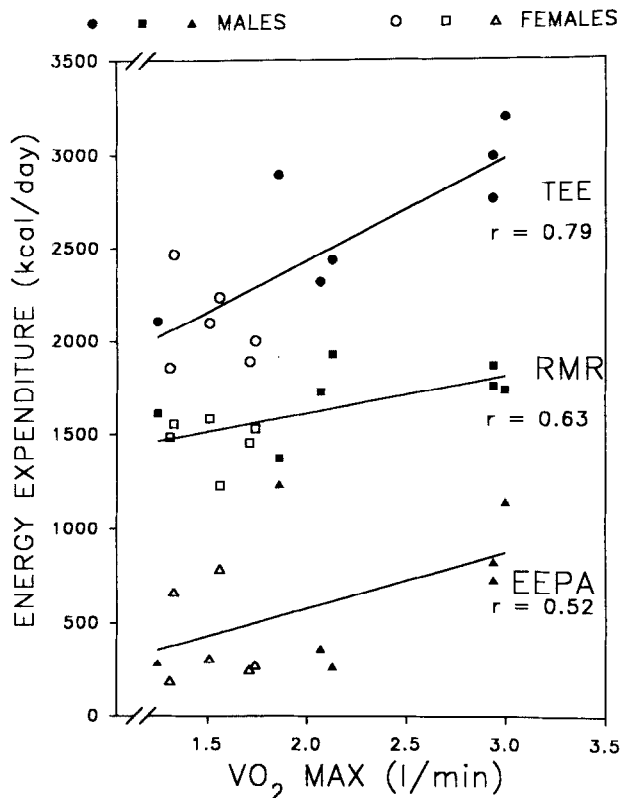


Fig 2. Correlation between various components of TEE and $\dot{V}O_2$ max. TEE (circles) is measured over 10 days using doubly labeled water; RMR (squares) is measured by respiratory gas exchange in the early morning after an overnight stay in the Clinical Research Center; EEPA (triangles) is derived from TEE and RMR using equation no. 5 (see Methods); $\dot{V}O_2$ max is determined from a cycle ergometer test to exhaustion.

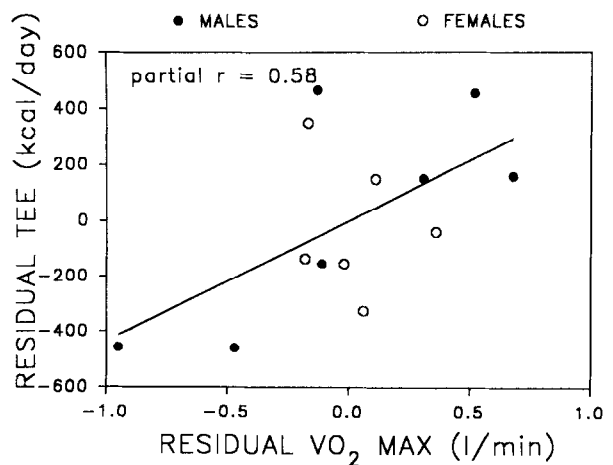


Fig 3. Partial correlation between TEE and $\dot{V}O_2$ max after adjustment for FFM. TEE is measured over 10 days using doubly labeled water; $\dot{V}O_2$ max is determined from a cycle ergometer test to exhaustion. For both variables, the residuals are the difference between the observed value and that predicted from its correlation with FFM.

obtained:

$$TEE(kcal/d) = (1.29 \times LTA) + (0.98 \times RMR) + 387 \quad (Eq\ 7)$$

The SE of the TEE estimated from equation no. 7 is ± 242 kcal/d.

Comparison of Reported Energy Intake With TEE

Figure 4 shows the relationship between self-reported energy intake and TEE measured over 10 days with doubly labeled water. There was a strong association between the two measures ($r = .77, P = .002$), although a consistent negative bias was observed, with the regression line lying below the line of identity (intake, kcal/d = [TEE \times 0.99] - 455), and the average 3-day reported energy intake was, on average, 21% \pm 18% below the measured value of TEE for the total group. Moreover, as shown in Fig 4, the degree of underreporting was significantly greater in women (reported intake, 31% \pm 18% below measured TEE) than in men (12% \pm 11% in men; $P = .031$).

The difference between intake and expenditure could not be explained by changes in energy balance, since there was no significant change in body mass over the 10-day study period (71.61 \pm 9.52 kg on day 1; 71.45 \pm 9.54 kg on day 10), and the mean individual body mass change was -0.17 \pm 0.49 kg (range, -1.03 to 0.52 kg). Furthermore, the individual weight change over the 10-day study period

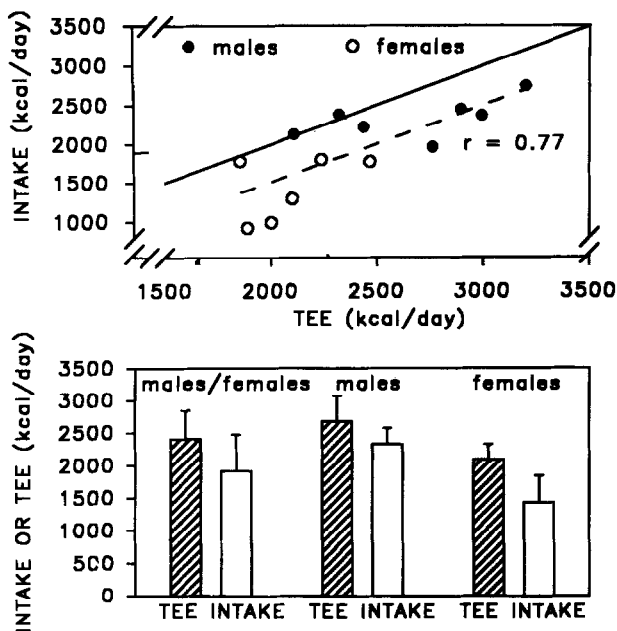


Fig 4. Association between reported energy intake and measured TEE. Intake is the self-recorded energy intake by administration of a 3-day food diary; TEE is measured over 10 days using doubly labeled water. (—) The line of identity for intake = TEE; (----) the observed regression line between the two variables. Lower figure compares TEE (▨) with reported energy intake (□) in males and females combined (left), males only (center), and females only (right).

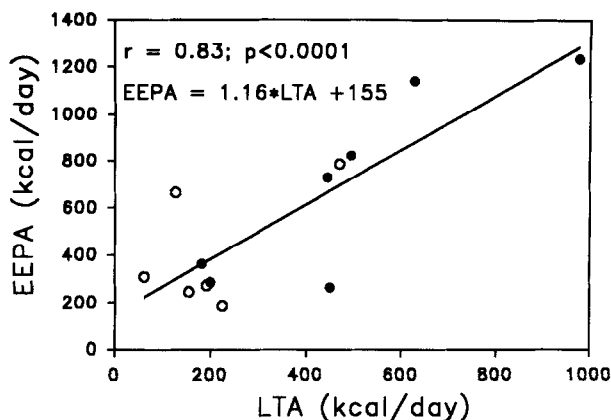


Fig 5. Association between EEPA and LTA assessed from a questionnaire. EEPA is averaged over a 10-day period, derived from measurements of TEE and RMR using equation no. 5; LTA is from the previous 12 months as assessed from the Minnesota Leisure Time Physical Activity Questionnaire.³¹

was not significantly related to the difference between measured TEE and reported energy intake.

Comparison of EEPA With LTA Derived From the Questionnaire

Figure 5 shows the association between EEPA derived from measurement of TEE and RMR and that derived from a 12-month recall questionnaire. The strong association between these two parameters (EEPA = [1.16 \times LTA] + 155 kcal/d; $r = .83, P < .0001$; SE of estimate, ± 208 kcal/d) provides new evidence regarding the validity of the leisure time questionnaire as a measure of daily LTA in this elderly population.

DISCUSSION

This study represents the first attempt to characterize TEE with doubly labeled water in free-living healthy elderly persons. The new findings are: (1) TEE is highly variable, due principally to high interindividual variation in daily physical activity; (2) VO_{2max} is a significant predictor of TEE for this population; and (3) healthy older individuals underreport habitual energy intake, with this effect being more pronounced in women.

TEE in Healthy Elderly Persons

A high degree of interindividual variation in TEE was observed (range, 1,856 to 3,200 kcal/d; coefficient of variation, $\pm 18.2\%$) in these elderly subjects. As seen in Table 3, this was a reflection of interindividual variation both in RMR (range, 1,227 to 1,930 kcal/d; coefficient of variation, $\pm 12.4\%$) and EEPA (range, 187 to 1,235 kcal/d; coefficient of variation, $\pm 63.7\%$). This wide variation presents a potential problem for formulating effective guidelines for energy requirements. Since the doubly labeled water technique does not lend itself to epidemiologic field use because of the cost and time involved, suitable physiological markers for TEE must be identified if energy requirements are to be accurately predicted.

The data currently presented examine the relationships between TEE and body composition, RMR, LTA by questionnaire, reported energy intake, and $\dot{V}O_2\text{max}$ within a group of free-living older subjects, in an attempt to identify suitable physiological markers for TEE. We found that TEE was most significantly related to $\dot{V}O_2\text{max}$ (Table 4, Fig 2), and this relationship was independent of differences in FFM (Fig 3). In fact, $\dot{V}O_2\text{max}$ alone accounted for 79% of the variation in TEE in this group of healthy elderly subjects. This finding can be interpreted in two ways: (1) the increased TEE, associated with a physically active life-style, leads to a higher $\dot{V}O_2\text{max}$ or, alternatively, (2) those individuals with a higher $\dot{V}O_2\text{max}$, as a result of genetic factors and/or regular participation in physical activity, engage in physical activities more frequently because of the higher work capacity.

Although we have previously reported a significant relationship between RMR and $\dot{V}O_2\text{max}$ (independent of FFM) in older individuals,² we were surprised to find that the correlation between TEE and $\dot{V}O_2\text{max}$ was stronger than that between TEE and FFM. Our results should not be interpreted as implying that FFM was not a significant predictor of TEE, because of the significant univariate correlation ($r = .64, P = .018$). The fact that FFM was not an independent predictor in multivariate analysis suggests a probable interaction between $\dot{V}O_2\text{max}$ and FFM, in which the effect of FFM on TEE is mediated by its covariance with $\dot{V}O_2\text{max}$. The practical implication of this finding is that $\dot{V}O_2\text{max}$ should be considered a useful physiological marker for TEE and, therefore, a useful variable for the determination of energy requirements in healthy elderly persons.

Information on EEPA in elderly persons has previously been limited to data derived from activity diaries or motion sensors.^{8,32} This component of TEE includes exercise, voluntary physical activity, and spontaneous physical activity (fidgeting). By measurement of TEE with doubly labeled water in combination with measurement of RMR and an estimation of the thermic response to meals, we were able to estimate EEPA more directly and unobtrusively than has previously been possible (see Methods). The data demonstrate that in an active and healthy group of elderly subjects, EEPA is the main factor contributing to individual variation in TEE. In the present study, EEPA ranged from 187 to 1,235 kcal/d, and contributed from 10% to 43% of TEE. Despite the wide interindividual variation, EEPA could be accurately predicted from the LTA questionnaire (Fig 5). This was a surprising finding, given the relatively simple task of estimating LTA from a 30-minute structured interview. The implication of this finding is the effective validation of this questionnaire as an estimate of the energy expended in leisure time. This is reassuring, given that many epidemiological studies have previously shown that high LTA, as derived from the same questionnaire used in this study, protects against cardiovascular disease.³³ Furthermore, the use of physical activity questionnaires may also provide additional information for estimating energy requirements in older persons.

Since RMR declines with age^{1,3-5} and elderly people are

generally less active,^{8,9} it would seem apparent that TEE would be lower in the elderly. For example, Vaughan et al⁴ recently showed that 24-hour energy expenditure measured in a room calorimeter was 13% lower in elderly persons ($1,861 \pm 284$ kcal/d) when compared with younger individuals ($2,144 \pm 351$ kcal/d). However, interestingly, they did not find age differences in spontaneous physical activity as measured in a room calorimeter. Although such studies provide valuable information on differences in 24-hour sedentary energy expenditure in younger and older persons under confined living conditions, they do not provide information on age-related differences in free-living daily energy expenditure.

We therefore compared the present data on free-living TEE in the older subjects with data in younger subjects. Data in older men was compared with 17 younger (aged 22.1 ± 3.7 years) men (Goran et al, unpublished). The younger men had a significantly lower body mass (68.4 ± 8.3 kg; $P = .02$) and TEE was not significantly different between younger and older men ($2,849 \pm 518$ kcal/d, 1.73 ± 0.25 times RMR in younger males ν $2,675 \pm 394$ kcal/d, 1.58 ± 0.31 times RMR in older males). However, TEE was approximately 18% lower in the older subjects when expressed per kg body mass (41.6 ± 5.2 kcal/d/kg body mass in younger men; 35.2 ± 7.4 kcal/d/kg body mass in older men, $P = .048$) or per kg FFM, as derived from total body water (55.5 ± 6.8 kcal/d/kg FFM in younger men; 47.2 ± 7.4 kcal/d/kg FFM in older men, $P = .017$). In addition, the presently reported data in the seven healthy elderly men were compared with baseline values in seven healthy younger men (mean age, 23.7 years) recently reported by Roberts et al.³⁴ The two groups were surreptitiously matched for body mass (76.3 ± 12.4 kg in the younger subjects, 77.1 ± 7.4 kg in the older subjects), but TEE was 20% lower in the older men ($2,675 \pm 395$ kcal/d; 1.58 ± 0.31 times RMR) compared with the younger men ($3,321 \pm 490$ kcal/d; 1.85 ± 0.03 times RMR).

For comparing age effects in women, the presently reported data were compared with the six younger (aged 24.8 ± 6.9 years) control subjects in the study of Casper et al.³⁵ The younger women weighed significantly less than the older women (56.5 ± 4.9 kg in younger women, 65.2 ± 7.8 kg in older women; $P = .048$), but the two groups were comparable with respect to FFM, as derived from total body water (39.6 ± 7.4 kg in younger women, 41.5 ± 2.9 kg in older women). There was no significant difference between young and old women in TEE ($1,985 \pm 352$ kcal/d in younger women ν $2,092 \pm 231$ kcal/d in older women), even when expressed as a function of RMR (1.50 ± 0.2 times RMR in younger women ν 1.43 ± 0.22 times RMR in older women), body mass (35.2 ± 6.2 kcal/d/kg body mass in younger women ν 32.5 ± 5.6 kcal/d/kg body mass in older women), or FFM (50.1 ± 8.5 kcal/d/kg FFM in younger women ν 52.0 ± 7.4 kcal/d/kg FFM in older women).

Taken together, these age-related comparisons imply that measurement of TEE in a room calorimeter may blunt age-related differences in spontaneous physical activity, due to the artificial nature of the living arrangements. On

the other hand, when TEE is measured under free-living conditions, age-related reductions are more apparent in men than in women. However, this finding is limited to the comparison of relatively low subject sizes and by the fact that interlaboratory comparisons are hindered by the variation in methodology for calculating and expressing TEE for comparative purposes.

Energy Requirements in Healthy Elderly Persons

An important application of this study is the relevance of the findings to the determination of daily energy requirements in healthy elderly subjects. Equations have previously been developed for the estimation of daily energy requirements in elderly men and women, based on either (1) reported values of energy intake^{7,32} or (2) application of an activity factor, derived from a crude assessment of the subject's physical activity level, to a measured or an estimated level of resting energy requirements.^{13,36}

However, the present results suggest that consideration of an individual's level of $\dot{V}O_2\max$ provides useful information to more accurately determine energy requirements for this population on an individual basis. This statement is based on the robust association between $\dot{V}O_2\max$ and TEE discussed above, and two additional lines of evidence. First, we have shown that reported energy intake underestimates TEE to a highly variable degree, and is more pronounced in women. This finding therefore casts doubt on the utility of recorded intake data to accurately predict energy requirements in healthy elderly persons. Second, the measured activity factor in these elderly subjects was highly variable (1.25 to 2.11) and was not significantly related to any of the physiological parameters under examination. Thus, knowledge of RMR is not necessarily a prerequisite for estimating energy requirements, since it only explains 42% of variation in TEE (Table 4).

The optimal approach to deriving equations for predicting energy requirements is to identify suitable physiological markers for an individual's level of TEE as measured under free-living conditions. Stepwise regression analysis of the data generated two useful equations for predicting TEE in the subjects under investigation. The first shows that $\dot{V}O_2\max$ and LTA by questionnaire (Equation no. 6) can explain 86% of the biological variation in TEE, and can predict TEE with an SE of ± 217 kcal/d. Also, LTA by questionnaire in combination with RMR (Equation no. 7) can explain 83% of the biological variation in TEE, and can predict TEE with an SE of ± 247 kcal/d. The limitation of these two equations is that they are based on observations in a small group of subjects and thus need to be replicated

in a larger sample of healthy older individuals. Thus, the prediction equations currently offered in this report are not meant to be applied to the population at large. At present, the purpose of these equations is to offer the means to compare data from future studies.

As seen in Fig 4, self-reported energy intake in healthy elderly subjects is significantly lower than the measured value of TEE, and there was no evidence to suggest that the subjects were actually consuming less calories than they were expending (ie, no evidence of energy imbalance). The underreporting of energy intake is consistent with previous reports in younger populations³⁷ and extends this observation to include elderly subjects. The degree of underreporting of energy intake was significantly greater in women than in men, but showed no significant association with body fatness, as has been previously reported,³⁷ or with RMR, TEE, physical activity, or $\dot{V}O_2\max$. Taken together, the underreporting bias and the gender effect demonstrate the poor validity of reported intake values for predicting TEE and/or energy requirements in older persons. In fact, when reported intake and sex are used to predict TEE, the total adjusted *r* value is .71, and the SE of the estimate is 307 kcal/d, compared with a total adjusted *r* value of .86 and an SE of the estimate of 217 kcal/d when $\dot{V}O_2\max$ and LTA are used to predict TEE. These findings suggest that reported intake and gender are less powerful predictors of TEE compared with indicators of physical activity such as $\dot{V}O_2\max$ and LTA by questionnaire.

In summary, TEE varies greatly within healthy elderly persons. The observed wide variation in activity level suggests that assessment of individual energy requirements using subjective activity factors is not applicable in this elderly population. Moreover, self-recorded intake underestimates daily energy needs in healthy elderly persons. Finally, the strong correlation between TEE and $\dot{V}O_2\max$ suggests that $\dot{V}O_2\max$ should be considered as an important predictor of energy requirements in healthy older individuals.

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