Endurance training does not enhance total energy expenditure in healthy elderly persons

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Goran, Michael I., and Eric T. Poehlman. Endurance training does not enhance total energy expenditure in healthy elderly persons. Am. J. Physiol. 263 (Endocrinol. Metab. 26): E950–E957, 1992.—Physical exercise is prescribed to older individuals to increase cardiovascular fitness and improve body composition. However, there is limited information on the effect of exercise on total energy expenditure (TEE) and its components. We therefore determined the effects of short-term endurance training in 11 elderly volunteers (56–78 years) on changes in 1) TEE, from doubly labeled water; 2) resting metabolic rate (RMR), from respiratory gas analysis; 3) the energy expenditure of physical activity (EEPA), aside from that associated with the training program, and 4) body composition from a combination of body density with total body water. Endurance training increased maximum oxygen consumption (VO2max) by 9% (2.00 ± 0.67 to 2.17 ± 0.64 l/min; \( P < 0.05 \)) and RMR by 11% (1,596 ± 214 to 1,763 ± 170 kcal/day; \( P < 0.01 \)). There was no significant change in TEE (2,408 ± 478 to 2,479 ± 497 kcal/day) before and during the last 10 days of endurance training because of a 62% reduction in EEPA (571 ± 386 to 340 ± 63 kcal/day; \( P < 0.01 \)). There was no change in body mass, but fat mass decreased (21.6 ± 6.6 to 20.7 ± 6.6 kg; \( P < 0.05 \)). The increase in fat-free mass (49.5 ± 9.0 to 50.4 ± 9.1 kg; \( P < 0.05 \)) was explained by an increase in body water (35.9 ± 6.5 to 36.8 ± 6.3 kg; \( P < 0.05 \)). We conclude that in healthy elderly persons, endurance training enhances cardiovascular fitness, but does not increase TEE because of a compensatory decline in physical activity during the remainder of the day.

ageing; physical activity; body composition; physical fitness; exercise

THE AGING PROCESS is associated with several deleterious changes in body composition and whole body energy metabolism. These changes include an increase in adiposity (6), a loss of muscle mass (6), a decline in physical activity (5, 14), and a fall in resting metabolic rate (14, 18, 19). It is unclear whether these changes are due to the aging process per se or are more reflective of changes in lifestyle. Exercise is frequently prescribed to elderly persons to improve body composition, enhance energy expenditure, and increase functional independence.

Endurance exercise is generally thought to increase total energy expenditure because of the direct energy cost of the exercise itself, the energy expenditure during the immediate postexercise period (1), and possibly an elevation in resting metabolic rate (15), although this effect is not seen in all studies (12). It is unknown whether exercise participation affects the daily energy cost of other physical activities during the remainder of the day. The energy expenditure associated with daily physical activities includes the energy cost required for the activities of daily living, exercise, spontaneous physical activity, and fidgeting. This component of daily energy expenditure has been shown to contribute a total of 138 to 688 kcal/day in young males when measured in a room calorimeter (22). These values are probably an underestimate of the true energy cost of daily physical activity because of the confined nature of living in a room calorimeter. Under free-living conditions, the energy expenditure of physical activity can only be derived by knowledge of the difference between total energy expenditure and the sum of the energy costs of the resting metabolic rate, the endurance exercise, and the thermic effect of feeding.

The primary purpose of this paper is to provide new information on adaptive changes in the components of daily energy expenditure in free-living healthy elderly persons in response to short-term endurance training, and in particular to determine whether elderly subjects become more or less physically active during the remainder of the day as a result of endurance training. The major finding is that vigorous endurance training does not increase total energy expenditure in older persons because of a compensatory reduction in physical activity during the remainder of the day. This finding raises new questions regarding the clinical utility of vigorous endurance exercise to enhance total energy expenditure in older individuals.

METHODS

Subjects. Data from 11 older individuals (age 56–78 years; 5 females and 6 males) are presented. Preexercise, baseline data are presented in Table 1. In addition, baseline data from these subjects was used in an analysis of the factors determining total energy expenditure and energy requirements in the elderly (8), and two of the subjects lived at the Clinical Research Center for the first and last 10 days as part of another study of covert monitoring of food intake (16). All subjects were recruited from the Burlington, Vermont, area by newspaper advertisements and radio announcements, and were in excellent general health as defined by the following criteria: 1) normal resting and exercise stress test electrocardiograms, 2) resting blood pressure <140/90, 3) not presently taking any prescribed or over-the-counter medication affecting cardiovascular or metabolic function, 4) absence of family history of diabetes, 5) absence of obesity as defined by a body mass index below the 85th percentile for sex and age using standard tables (13), 6) weight stability (±2 kg) by medical history within the past year, and 7) absence of any abnormal liver enzyme or lipid value from a routine blood chemistry screening. The nature, purpose, and possible risks of the study were carefully explained to each subject before obtaining their written consent to participate. The experimental protocol was approved by the Committee on Human Research for the Medical Sciences of the University of Vermont, and the advisory board of the Clinical Research Center at the University of Vermont.

Outline of protocol. A baseline measurement of total energy expenditure was performed during free-living conditions for 10 days before commencement of the training program. On the ninth day of this period, subjects were admitted for an overnight visit to the Clinical Research Center. In the morning, a second void urine was collected to mark the end of the doubly labeled
water study, and tests were performed in the postabsorptive state for measurement of resting metabolic rate, body composition, and maximal aerobic capacity ($V_{O_2,max}$).

After these test procedures, subjects began a supervised endurance training program consisting of cycling exercise three times per week for 8 wk. Ten days before the end of the training program, subjects were redosed with doubly labeled water for reassessment of total energy expenditure. During this 10-day period, nine of the subjects attended four exercise sessions while two subjects attended only two sessions because of scheduling considerations. On the ninth day, subjects returned for an overnight visit to the Clinical Research Center for follow-up testing of resting metabolic rate, body composition, and $V_{O_2,max}$. The day of follow-up testing was at least 2 days after the last exercise session, as this delay has been shown to eliminate the residual effects of exercise on resting metabolic rate and hormonal status (17).

Outline of endurance training program. The endurance training program involved cycling three times per week, beginning at a net energy expenditure of 150 kcal per session at 60% of $V_{O_2,max}$ in week 1, and with incremental increases in duration and intensity to eventually reach an expenditure of 300 kcal per exercise session three times per week at 85% of $V_{O_2,max}$ by week 8, as previously described (15). The exercise prescription was adjusted during the fourth week of training to take into account the increase in $V_{O_2,max}$ and to maintain the prescribed energy expenditure of the exercise program. Exercise prescriptions were derived from the linear relation between heart rate and $O_2$ consumption ($V_{O_2}$) established for each individual during a cycle ergometer test for $V_{O_2,max}$. From this test, a net energy expenditure (total cost of exercise minus resting metabolic rate) was calculated. All exercise sessions were supervised by a physical therapist, who was assisted by at least two undergraduate students, who monitored heart rate every 5 min in each subject to assure compliance to the exercise prescription. No injuries or health disorders were noted during the exercise program, and no modification in the protocol had to be introduced. All subjects attended all of the exercise sessions.

Measurement of total energy expenditure. Total energy expenditure was measured under free-living conditions for 10 days using the doubly labeled water technique before and during the last 10 days of the training program. The following protocol was designed in accordance with the guidelines offered by the International Dietary Exchange Consultant Group for use of the doubly labeled water technique in humans (21).

Subjects reported to the Clinical Research Center in the morning after an overnight fast for collection of baseline urine and plasma samples (10 ml), followed by a mixed oral dose of doubly labeled water [10% $H_{18}O$ (Cambridge Isotope Laboratories, Cambridge, MA) mixed with 99.8% $H_2O$ (Icon Services, Summit, NJ) in a ratio of 20:1] at a dose of 0.15 g of $H_{18}O$ and 0.075 g of $H_2O$ per kilogram body weight. A 1:400 dilution of the dose was weighed and prepared for each subject at the time of dosing, and samples of the water used for the dilution and the diluted dose were saved with each sample set for analysis. The subjects were instructed to collect and freeze the second void urine sample the next 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°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 $H_{18}O$ and $H_2O$ using the CO$_2$ equilibration technique (4) and the off-line zinc reduction method (10), respectively. 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$_2$ with overnight shaking at room temperature. CO$_2$ was introduced into a VG SIR-II isotope ratio mass spectrometer via an automated carousel sample system (VG, Middlewich, Cheshire, UK) and analyzed for the ratio of mass 46:44. The average standard deviation for 91 sets of triplicate samples analyzed for $H_{18}O$ enrichment (average enrichment, 93.795%) was +0.39%, and the standard deviation was independent of the enrichment of the sample analyzed ($r = 0.33, P > 0.05$).

The zinc reduction method was similar to that previously described (7), and used the quartz reduction vessels described by Wong and Klein (29) and a ratio of 3-μl sample (undistilled) with 100 mg of zinc (Biogeochemical Laboratories, Bloomington, IN). Reduction was achieved by heating at 500°C for 30 min in an aluminum block (Biogeochemical Laboratories). The ratio of mass 3 to mass 2 in the hydrogen gas produced was analyzed using a VG SIR-II isotope ratio mass spectrometer equipped with a 20-port automated inlet system. With the use of this method, the average standard deviation for 65 sets of triplicate $H_2O$ sample analysis was ±2.82% at a mean sample enrichment of 333.997%, and the standard deviation was independent of the enrichment of the sample ($r = 0.24, P > 0.05$).

Turnover rates and time zero dilution spaces of $H_{18}O$ and $H_2O$ were calculated from the slope and intercept of the semi-logarithmic plot of isotope enrichment in urine vs. time after dosing. CO$_2$ production rates were calculated using the equation

$$r_{CO_2} (mol/day) = 0.4554 \times (D_O k_O - D_H k_H)$$

where $D_O$ and $D_H$ are the individual, zero-time extrapolated dilution spaces of $H_{18}O$ and $H_2O$ in moles, and $k_O$ and $k_H$ are the turnover rates of $H_{18}O$ and $H_2O$ in days$^{-1}$.

Isotopic dilution spaces were calculated using the equation (21)

$$N (mol) = \frac{[(W \times A \times (E_{water} - E_{diluted})) / 18.02 \times a \times (E_{post} - E_{pre})]} \approx$$

where $N$ is isotopic dilution space in moles; $W$ is the weight of water used to make the dilution of the dose; $A$ is weight of dose administered; $a$ is the weight of water diluted; $E_{water}$, $E_{pre}$, and $E_{post}$ are enrichments (in %) of the diluted dose, the water used for the dilution, urine at time zero, and urine before dose administration. Oxygen consumption was derived by dividing CO$_2$ production rate by the food quotient, derived on an individual basis from the composition of the diet (as measured from a 3-day self-reported diary) using the equations of Blackburn et al. (3). Total energy expenditure was calculated using Eq. 12 of De Weir (5a).

A number of studies have shown that the doubly labeled water method is valid under various states of physical activity by comparing energy expenditure in very active people with either chamber calorimetry (28) or energy intake/balance techniques (9). These studies suggest that the addition of physical exercise to the daily regimen does not violate any of the inherent assumptions in the doubly labeled water technique.

Measurement of resting metabolic rate. Resting metabolic rate was measured for 45 min in the early morning after an overnight fast by respiratory gas analysis using a ventilated hood system for breath collections as previously described (15). The reproducibility of resting metabolic rate in older volunteers in our laboratory has a coefficient of variation of 4.3%.

Derivation of energy expenditure of physical activity. The energy expenditure of physical activity, aside from that associated with endurance training, was derived by the difference between total energy expenditure and the sum of the daily energy costs of 1) the resting metabolic rate; 2) the thermic response to meals, estimated to be 10% of total energy expenditure (19) and; 3) the endurance training program. The average daily energy cost of the prescribed endurance exercise during the doubly labeled water study was 150 kcal/day (300 kcal/session times 5 sessions
over 10 days), and is probably a slight underestimate because it
does not include warm-up activity or the residual energy expen-
diture associated with postexercise recovery (1).  

Measurement of body composition. Body composition was
estimated from the three-compartment model of Siri (25),
which combines body density with total body water. This tech-
nique has been shown to improve the precision of body fat
estimates over that obtained from either densitometry or total
body water alone (25). Total body density was obtained
from underwater weighing, with simultaneous measurement
of residual lung volume by helium dilution as previously described
(18). Reproducibility of this technique has a coefficient of
variation of 4.1% in elderly subjects in our laboratory. Total
body water was calculated from the mean dilution space of H\textsubscript{2}\textsuperscript{18}O and \textsuperscript{2}H\textsubscript{2}O after adjusting them by factors of 1.01
and 1.04, respectively, to account for isotope exchange (23). The
values of body density (g/ml) and body water (as a percentage
of body mass) are used to calculate body fat in the following
equation (25)

\[
\% \text{body fat} = \frac{2.118}{\text{density}} - (0.78 \times \% \text{body water}) - 1.354
\]

Fat-free mass was calculated as body mass minus fat mass,
and fat-free mass minus body water mass was used as an esti-
mate of mineral plus protein mass. Protein plus mineral mass is
a more reflective estimate of metabolically active tissue than
fat-free mass.

Other physiological measurements. \textit{V}O\textsubscript{2} max was measured by
a bicycle ergometer test to exhaustion as previously described
(15). Attainment of \textit{V}O\textsubscript{2} max requires meeting at least two of the
following criteria: 1) attainment of an age-predicted maximal
heart rate, 2) a maximal respiratory exchange ratio >1.0, and/or
3) no further increase in \textit{V}O\textsubscript{2}, despite an increase in work load.
Self-reported energy and macronutrient intake were estimated
from a 3-day, self-administered food diary, which included two
weekdays and one weekend day, as previously described (20).

Statistics. Mean values, standard deviations (SD), and
ranges are presented for all measures and parameters. Differe-
ces in level of change between males and females were as-
11 ed by analysis of variance. The paired \( t \) test was used to
examine the statistical significance of changes in physiological
parameters in response to the exercise intervention. The Pear-
s son product-moment correlation was used to derive the level of
association between the magnitude of change of variables with
one another. All statistical and data manipulations were per-
fomed on a personal microcomputer using either Lotus 1-2-3
(Lotus, Cambridge, MA) or Statplan (The Futures Group,
Washington, DC) software packages.

RESULTS

The subjects in this study were 11 elderly volunteers (5
females, 6 males) with a mean age of 66 ± 6 years (range
56 to 78). The individual subject characteristics with re-
spect to age, height, and body composition are shown in
Table 1. There were no significant differences between
males and females with respect to age, height, body mass,
and fat mass, although males had significantly greater
fat-free mass than females, and percent body fat was
significantly higher in females.

Table 2 displays the data before and after exercise
training for variables associated with the doubly labeled
water technique. During the exercise period, there was a
small but significant drop in the rate of \textsuperscript{2}H\textsubscript{2}O turnover and a
3% (\( P < 0.05 \)) expansion of the \textsuperscript{2}H\textsubscript{2}O distribution
space, with no significant change in either the \textsuperscript{2}H\textsubscript{2}O
turnover rate or the \textsuperscript{18}O distribution space. Thus the
ratio of the \textsuperscript{2}H\textsubscript{2}O to \textsuperscript{18}O distribution space was signif-
icantly greater in the studies performed during endurance
training.

The individual data for the absolute changes in kilo-
calories per day for total energy expenditure, resting met-
bolic rate, and the energy expenditure of physical activity
are shown in Fig. 1, and the group data are sum-
morized in Fig. 2. There was no change in total energy
expenditure after 8 wk of endurance training (2,408 ± 478
to 2,474 ± 497 kcal/day) despite a significant increase in
resting metabolic rate (1,596 ± 214 to 1,763 ± 170 kcal/
day) and the average daily energy cost of the endurance
training (equivalent to 150 kcal/day when averaged over
the 10-day doubly labeled water study period). Thus the
energy expenditure of physical activity, during nonexer-
cising time, was significantly reduced (571 ± 386 vs. 340
± 452 kcal/day) during the last 10 days of endurance
training compared with pretraining levels. Correlation
analysis did not reveal any significant associations be-
tween individual change in energy expenditure and initial
fitness, fatness, leanness, or age of subject. In addition,
there was no significant gender effect for changes in total

<table>
<thead>
<tr>
<th>Subject, Sex</th>
<th>Age, yr</th>
<th>Height, cm</th>
<th>BM, kg</th>
<th>FFM, kg</th>
<th>%Fat</th>
<th>FM, kg</th>
</tr>
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<tbody>
<tr>
<td>F1</td>
<td>65</td>
<td>169</td>
<td>60.06</td>
<td>42.81</td>
<td>38.01</td>
<td>26.25</td>
</tr>
<tr>
<td>F2</td>
<td>60</td>
<td>161</td>
<td>61.90</td>
<td>38.56</td>
<td>37.71</td>
<td>23.34</td>
</tr>
<tr>
<td>F3</td>
<td>67</td>
<td>167</td>
<td>60.78</td>
<td>38.79</td>
<td>36.17</td>
<td>21.99</td>
</tr>
<tr>
<td>F4</td>
<td>56</td>
<td>166</td>
<td>79.50</td>
<td>45.67</td>
<td>42.55</td>
<td>33.83</td>
</tr>
<tr>
<td>F5</td>
<td>56</td>
<td>166</td>
<td>58.93</td>
<td>39.02</td>
<td>33.79</td>
<td>19.91</td>
</tr>
<tr>
<td>M1</td>
<td>66</td>
<td>166</td>
<td>59.32</td>
<td>38.56</td>
<td>36.17</td>
<td>21.99</td>
</tr>
<tr>
<td>M2</td>
<td>66</td>
<td>167</td>
<td>60.29</td>
<td>38.56</td>
<td>36.17</td>
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<tr>
<td>M3</td>
<td>78</td>
<td>171</td>
<td>64.16</td>
<td>45.67</td>
<td>42.55</td>
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</tr>
<tr>
<td>M4</td>
<td>69</td>
<td>173</td>
<td>79.76</td>
<td>55.17</td>
<td>50.83</td>
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<tr>
<td>M5</td>
<td>65</td>
<td>167</td>
<td>71.11</td>
<td>53.11</td>
<td>50.83</td>
<td>24.59</td>
</tr>
<tr>
<td>M6</td>
<td>73</td>
<td>187</td>
<td>60.48</td>
<td>53.11</td>
<td>50.83</td>
<td>24.59</td>
</tr>
<tr>
<td>Mean ± SD (group)</td>
<td>66±6</td>
<td>170±9</td>
<td>71.11±5.50</td>
<td>49.53±2.02</td>
<td>36.45±1.89</td>
<td>21.56±1.64</td>
</tr>
<tr>
<td>Mean ± SD (females)</td>
<td>63±5</td>
<td>166±3</td>
<td>66.03±7.80</td>
<td>40.92±3.16</td>
<td>37.65±2.21</td>
<td>25.06±2.41</td>
</tr>
<tr>
<td>Mean ± SD (males)</td>
<td>60±7</td>
<td>175±10</td>
<td>75.32±4.92</td>
<td>56.65±4.99</td>
<td>24.44±7.40</td>
<td>18.67±6.59</td>
</tr>
</tbody>
</table>

Subject characteristics in 11 healthy elderly subjects (5 females, 6 males). BM, body mass; FFM, %fat, and FM are fat-free mass, percent body
fat, and fat mass, respectively, as estimated from combination of total body density and total body water (see METHODS). * Significant difference
(\( P < 0.05 \)) between males and females.
Table 2. Changes in doubly labeled water-related parameters in response to an 8-wk exercise program in healthy elderly individuals

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Preexercise Mean ± SD</th>
<th>Postexercise Mean ± SD</th>
<th>Mean Change ± SD (Range of Change)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$h_{H_2}O$</td>
<td>-0.0892±0.0169</td>
<td>-0.0839±0.0165*</td>
<td>0.0053±0.0072 (-0.0056 to 0.0141)</td>
</tr>
<tr>
<td>$k_{H_2}O$</td>
<td>-0.1151±0.0187</td>
<td>-0.1105±0.0185</td>
<td>0.0046±0.0078 (-0.0062 to 0.0162)</td>
</tr>
<tr>
<td>$D_{H_2}O$</td>
<td>2,087.9±380.4</td>
<td>2,152.7±370.7*</td>
<td>64.8±57.0 (-15.0 to 194.0)</td>
</tr>
<tr>
<td>$D_{H_2}O$</td>
<td>1,990.6±362.3</td>
<td>2,033.1±348.1</td>
<td>42.5±45.7 (-46.9 to 172.8)</td>
</tr>
<tr>
<td>$D_{H_2}O/D_O$</td>
<td>1.049±0.01</td>
<td>1.069±0.009*</td>
<td>0.009±0.013 (-0.017 to 0.026)</td>
</tr>
<tr>
<td>$r_{CO_2}$</td>
<td>19.3±3.56</td>
<td>19.85±3.90</td>
<td>0.51±2.12 (-3.20 to 3.64)</td>
</tr>
</tbody>
</table>

$k_{H_2}O$ and $k_{O_2}$ are turnover rates of $^2H_2O$ and $^2H_2O$. $D_{H_2}O$ and $D_{H_2}O$ are zero-time distribution spaces of $^2H_2O$ and $^2H_2O$, and $r_{CO_2}$ is $CO_2$ production rate (see METHODS for details of calculations). * Significant change by paired t test at $P < 0.05$.

energy expenditure, resting metabolic rate, and the energy expenditure of physical activity between males and females.

The individual changes in body composition are shown in Fig. 3 and summarized in Table 3. There was no significant change in body mass ($P > 0.1$), but there was a small but significant decrease in fat mass ($P < 0.05$). The increase in fat-free mass ($P < 0.05$) was explained by a small but significant increase in total body water ($P < 0.05$); therefore, there was no significant change in mineral mass plus protein mass. There were no significant differences between males and females for changes in body mass, fat mass, and fat-free mass.

Changes in total energy expenditure and change in the energy expenditure of physical activity were not significantly related to change in fat-free mass ($r = 0.26$ and 0.06, respectively) or change in fat mass ($r = 0.12$ and 0.31, respectively). However, change in total energy expenditure and change in the energy expenditure of physical activity had borderline correlations with individual body mass changes ($r = 0.58$, $P = 0.06$; and $r = 0.59$, $P = 0.06$, respectively).

Individual data for resting metabolic rate before and after endurance training, as a function of mineral plus protein mass, are shown in Fig. 4. Resting metabolic rate and mineral plus protein mass were related before ($r = 0.75$, $P = 0.008$) and after ($r = 0.74$, $P = 0.009$) endurance training. The increase in resting metabolic rate per kilogram of mineral plus protein mass is depicted by a displacement of the regression line upward after endurance training, with no change in slope (before training, resting metabolic rate = $62.3 ± 18.4 \times \text{mineral plus protein mass}$ + 744; after training, $RMR = (43.5 ± 13.3 \times \text{mineral plus protein mass}) + 1,171$).

There was a significant 10% increase in $V_{O_2\ max}$ after exercise training ($2.00 ± 0.67$ to $2.17 ± 0.64$ l/min; $P < 0.05$). According to a 3-day self-recorded intake diary, there was no significant change in reported energy intake (1,883 ± 595 kcal/day before exercise vs. 2,083 ± 489 kcal/day after exercise) or food quotient ($0.88 ± 0.03$ before exercise vs. $0.88 ± 0.02$ during exercise). There were no significant differences in males and females for changes in $V_{O_2\ max}$ and energy intake (data not shown).
We examined changes in the components of daily energy expenditure in healthy elderly individuals in response to endurance training. The new finding is that endurance training does not enhance free-living total energy expenditure. This finding was due to a significant decrease in the energy expended in physical activity during the remainder of the day, which negated the increase in energy expenditure arising from the higher resting metabolic rate and the energy cost of the exercise program. These findings provide new evidence that endurance exercise in elderly individuals may actually contribute to greater inactivity during nonexercising time.

Effects of endurance training on total energy expenditure. This study represents the first attempt to systematically examine adaptive changes in the components of daily energy expenditure in response to endurance training in elderly persons. It is generally assumed that endurance training leads to an increase in total energy expenditure because of the direct caloric cost of the exercise bout, the elevation in energy expenditure during the immediate postexercise period (1), and the elevation in resting metabolic rate, which we have consistently shown in older individuals (15, 16), although the latter finding remains controversial (12).

An important and variable component of total energy expenditure that has not previously been considered in the overall response to endurance exercise is the energy expended in daily physical activities, aside from that associated with the endurance training activity. Assessment of this component of energy expenditure has recently become possible with the ability to measure free-living total energy expenditure with the doubly labeled water technique. The daily energy expended in physical activities contributes from 138 to 685 kcal/day in younger individuals confined to a room calorimeter (22) and from 187 to 1,235 kcal/day during baseline measurements in the free-living elderly subjects in this study. It is unknown, however, whether subjects become more or less physically active during the remainder of the day as a result of endurance training, and whether such changes are of sufficient magnitude to impact on the overall net change in total energy expenditure.

With the use of the doubly labeled water technique, the present study revealed that free-living total energy expenditure was not significantly different during the last 10 days of the exercise program compared with baseline measurements. This was a surprising finding given the increase in energy expenditure due to the endurance training (equivalent to 150 kcal/day) and the 10% elevation in resting metabolic rate (equivalent to an increase of 167 kcal/day). It is unlikely that the failure to detect an increase in total energy expenditure was due to an inadequate sample size. Power analysis calculations show that with our sample size of 11 subjects we could have detected a 10% increase in total energy expenditure with a power of 0.84. Furthermore, we would have required a sample size of 113 subjects to prove that the observed 3% increase in total energy expenditure was significant. Even so, the physiological significance of such a small change in total energy expenditure would be questionable.

The fact that total energy expenditure was not increased during the last 10 days of endurance training suggests that other “energy-conserving” mechanisms are operative during the remainder of the day. The present results show that the energy expended in physical activities, aside from that associated with the endurance training, was reduced by an average of 62% (571 ± 386 to 340 ± 452 kcal/day) during the last 10 days of training (see Fig. 2). The reduction in energy expended for physical activity is likely due to a reduction in spontaneous physical activity and/or a reduction in voluntary physical activities during the 10-day measurement period. Decreases in spontaneous physical activity have been shown to occur in response to strenuous physical activity in animal studies (26, 27). In humans, however, there is little information on this topic other than that provided by Schulz et al. (24), who examined the effect of fitness level on 24-h sedentary energy expenditure in a room calorimeter. They found no differences in sleeping metabolic rate, 24-h energy expenditure, or spontaneous physical activity between trained and untrained individuals. However, these studies were not performed under free-living conditions, and the endurance-trained individuals were not permitted to continue with their exercise training activities during experimental observations.

It is conceivable that the level of exercise during the last week of training (3 h/wk at 85% of $\text{V} \text{O}_2$ max) was too vigorous, and thus fatigued the elderly participants during the remainder of the day. Subjective comments from the volunteers revealed that they found the last 2 wk of the endurance training difficult to complete. Our results are therefore important because they demonstrate that exercise participation does not necessarily provide caloric benefits by elevating total energy expenditure. From a clinical perspective, our results could be interpreted to indicate that vigorous endurance exercise should not be recommended to the elderly as the most efficient exercise prescription because of its blunting effect on physical activity during nonexercising time.

Our findings, however, should not be interpreted to
EFFECT OF EXERCISE ON TEE IN THE ELDERLY

Table 3. Change in body composition in response to an 8-wk endurance exercise program in healthy elderly persons

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Preexercise Mean ± SD</th>
<th>Postexercise Mean ± SD</th>
<th>Mean Change ± SD (Range of Change)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Body mass, kg</td>
<td>71.11±8.50</td>
<td>71.07±8.41</td>
<td>-0.04±0.59 (-0.86 to 0.84)</td>
</tr>
<tr>
<td>Body water, kg</td>
<td>35.85±6.52</td>
<td>36.79±6.31*</td>
<td>0.94±0.95 (-0.37 to 3.22)</td>
</tr>
<tr>
<td>Fat mass, kg</td>
<td>21.58±6.64</td>
<td>20.68±6.61*</td>
<td>-0.89±0.71 (-2.24 to 0.09)</td>
</tr>
<tr>
<td>%Fat</td>
<td>30.45±8.89</td>
<td>29.21±8.81*</td>
<td>-1.24±1.09 (-2.62 to 0.36)</td>
</tr>
<tr>
<td>Fat-free mass, kg</td>
<td>49.53±9.02</td>
<td>50.38±9.09*</td>
<td>0.85±1.01 (-0.95 to 2.02)</td>
</tr>
<tr>
<td>Mineral + protein mass, kg</td>
<td>13.68±2.88</td>
<td>13.60±2.88</td>
<td>-0.09±0.59 (-1.20 to 0.92)</td>
</tr>
</tbody>
</table>

Body water determined from isotope dilution; fat mass and fat-free mass determined from combination of density and total body water (see METHODS). * Significant change at P < 0.05 by paired t test.

Fig. 4. Relationship between resting metabolic rate (RMR) and mineral plus protein mass before (open circles, dashed line) and after (solid circles, solid line) an 8-wk exercise intervention in healthy elderly persons. RMR measured upon awakening by respiratory gas analysis. Mineral plus protein mass derived from combination of body density (underwater weighing) and total body water. See METHODS for more details.

indicate that all levels of endurance training will not increase total daily energy expenditure. Exercise prescriptions of lighter intensity and varying durations should be examined to verify their influence on total energy expenditure and its various components, since it is conceivable that a lower level of endurance training may increase energy expenditure of physical activity and total energy expenditure. Furthermore, despite the absence of an increase in total energy expenditure, a significant increase in VO\textsubscript{2 max} was observed in the present study. Thus, as long as the exercise is of sufficient intensity and duration, a “training effect” can be found regardless of changes in total energy expenditure in an older population.

We recently reported a strong correlation between total energy expenditure and VO\textsubscript{2 max} in elderly subjects, thus suggesting that VO\textsubscript{2 max} is a biological marker of total energy expenditure and individual energy requirements (8). The present data may appear inconsistent with this concept, since the increase in VO\textsubscript{2 max} in the present study did not result in any significant change in total energy expenditure. Based on our previously described relationship between total energy expenditure and VO\textsubscript{2 max} (8), we would predict that the increase in VO\textsubscript{2 max} in the present study (+0.17 l/min) would result in an increase in total energy expenditure of 93 kcal/day. This compares favorably with the observed nonsignificant increase of 66 kcal/day in the present study.

To our knowledge, only one other study has addressed the impact of exercise training on changes in the energy expenditure of physical activity in free-living individuals. Meijer et al. (11) used a variety of techniques to examine changes in total energy expenditure and the energy expenditure of physical activity in younger individuals who were training over 5 months for a half-marathon. Using accelerometry, it was concluded that endurance training had no effect on habitual physical activity during nonexercising time (11). In addition, data is presented in four males and four females using the doubly labeled water technique showing an increase in physical activity during nonexercising time in males but not in females. This data, however, is difficult to interpret because it is unclear how much of the increase in total energy expenditure is due to increase in habitual physical activity as opposed to the energy cost of the training regimen. In addition, the data in males is biased by an outlier who had a 42% increase in total energy expenditure after 20 wk of endurance training (11).

The fact that energy expenditure of physical activity is not directly measured in the present study, but derived from the difference between total energy expenditure and its components, raises the possibility that measurement error in either resting metabolic rate or total energy expenditure may introduce bias to the derived value for the energy expenditure of physical activity. For example, it is possible that the energy expenditure of physical activity was underestimated during exercise training because of an overestimation of resting metabolic rate. However, since resting metabolic rate was measured 48 h after exercise, the value obtained did not include any carry-over energy expenditure from the prior exercise bout. Thus the actual energy expenditure of physical activity during exercise training may be even lower than that reported. Another possible source of bias could be that sleeping metabolic rate increased by an amount greater than the reported increase in resting metabolic rate. This seems
unlikely, since it would require a dramatic increase in sleeping metabolic rate (200–300 kcal) over a short period of time (6–8 h) and resting metabolic rate was measured just after awakening. Moreover, Bingham et al. (2) reported no change in sleeping metabolic rate in response to a 9-wk training program in younger men and women.

Alternatively, the energy expenditure of physical activity could have been underestimated during the training period because of an overestimate of total daily expenditure. As shown in Table 4, CO₂ production rates, derived from the doubly labeled water technique, were consistent before and after exercise training, independent of the method of calculation. We also have no evidence that error was introduced to total energy expenditure values during the conversion from CO₂ production rates. This is based on the fact that the food quotient, from 3-day self-recorded diaries, was consistent before (0.88 ± 0.03) and during (0.88 ± 0.02) endurance training in this study and during covert monitoring of food intake in subjects living at the Clinical Research Center in a similar endurance training program (16). Collectively, it appears unlikely that systematic bias in the methodology affected the major conclusions reported.

Effects of endurance training on body composition. In a previous exercise intervention study in elderly people, we reported significant increases in resting metabolic rate, \( V_{\text{O}_2}\text{max} \), and sympathetic nervous system activity (15). One possible explanation for these changes could be a concomitant rise in fat-free mass, although this was not apparent using densitometry alone to determine body composition (15). In the present study, we used a three-compartment model involving the combination of total body water and body density (25) to examine changes in fat-free mass and fat mass induced by exercise training. Our findings suggest that endurance training in elderly persons induced a significant increase in fat-free mass (+0.85 ± 1.01 kg) and a significant decrease in fat mass (−0.89 ± 0.71 kg), in the absence of change in overall body mass. The increase in fat-free mass, however, was explained by an increase in total body water during training. Therefore, endurance training had no effect on the mass of mineral and protein in the body.

We were surprised to detect these small changes in body composition after only 8 wk of endurance training. This is probably a reflection of increased sensitivity of the combined density-total body water method to detect changes in body composition in response to physiological stimuli (25). The failure to detect these changes in previous studies performed in our laboratory (15) could reflect certain limitations in using densitometry alone to detect small changes in body composition. If density alone was used to determine body composition in the present experiment, we would have found no significant changes in fat mass (−0.27 ± 1.06 kg) or fat-free mass (0.23 ± 1.20 kg).

Knowledge of total body water in addition to total body density increases not only the accuracy and precision of the methodology but also the ability to detect physiological changes within individuals under different conditions (25). This is because all of the available equations used to convert body density to body fat assume a constant reference density for fat and fat-free tissue, whereas in effect these reference densities are influenced by various physiological conditions, for example, those induced by the exercise-trained state. The only assumption inherent in the density-total body water method is that the ratio of mineral to protein is constant at a value of 0.35, and large physiological fluctuations or changes in this ratio do not alter the computed body composition (25).

In summary, vigorous endurance training does not increase total energy expenditure in older persons. The increase in energy expenditure due to the elevation in resting metabolic rate and the direct energy cost of the training program is offset by a compensatory decline in energy expended in physical activities other than that associated with the training program. However, endurance training in elderly subjects induces favorable changes in body composition and \( V_{\text{O}_2}\text{max} \) which are apparent in the absence of a corresponding increase in total energy expenditure.

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REFERENCES


<table>
<thead>
<tr>
<th>Calculation</th>
<th>( r\text{CO}_2) mol/day (Preexercise)</th>
<th>( r\text{CO}_2) mol/day (Postexercise)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method 1</td>
<td>19.34±5.56</td>
<td>19.85±3.90</td>
</tr>
<tr>
<td>Method 2</td>
<td>19.80±6.08</td>
<td>19.99±3.96</td>
</tr>
<tr>
<td>Method 3</td>
<td>21.42±3.86</td>
<td>22.29±4.07</td>
</tr>
<tr>
<td>Method 4</td>
<td>21.08±3.91</td>
<td>22.33±3.99</td>
</tr>
</tbody>
</table>

\( r\text{CO}_2 \) is CO₂ production rate calculated using 4 different methods. Method 1 uses individual distribution spaces for both isotopes as derived from intercepts; method 2 assumes that the ratio between the two distribution spaces is fixed and equivalent to the group value for each of the two phases, and calculates total body water from plateau enrichment of \( H_2^{18}O \) in plasma 4 h after dosing; methods 3 and 4 both assume that the ratio of the two distribution spaces is fixed at the conventionally assumed value of 1.04:1.01, using a value for total body water derived from either intercept data (method 3) or plateau data (method 4).


