Endurance training increases metabolic rate and norepinephrine appearance rate in older individuals

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POEHLMAN, Eric T., and Elliot Danforth, Jr. Endurance training increases metabolic rate and norepinephrine appearance rate in older individuals. Am. J. Physiol. 261 (Endocrinol. Metab. 24): E233–E239, 1991.—We examined the effects of an 8-wk endurance training program (cycling exercise) on resting metabolic rate (RMR) and norepinephrine (NE) kinetics in 19 older persons (64 ± 1.6 yr). Before and after training, RMR, NE kinetics, maximal O2 consumption (V\textsubscript{O\textsubscript{2 max}}), body composition, supine blood pressure, estimated energy intake, and fasting levels of glucose, insulin, and thyroid hormones were measured. RMR increased 10% after training. Resting concentrations of NE increased 24% after training due to a 21% increase in NE appearance rate and no change in NE clearance. Training increased V\textsubscript{O\textsubscript{2 max}} (14%; \(P < 0.01\)) and energy intake (12%; \(P < 0.01\)), whereas no change was noted in body composition. Supine blood pressure and plasma glucose were lower after training, whereas no change was noted in fasting levels of plasma insulin. The increase in RMR was associated with a higher rate of NE appearance (\(r = 0.57\); \(P = 0.05\)) and with increase in energy intake (\(r = 0.56\); \(P = 0.05\)). Together these two factors accounted for 49\% (\(r^2\)) of the variation of the change in RMR. Changes in blood pressure were not associated with changes in NE kinetics. We conclude that endurance training increases total energy expenditure in older individuals by the direct energy cost of physical activity and by elevating RMR. This increase is partially mediated by an increased NE appearance rate and increased food intake in healthy older individuals.

norepinephrine appearance and clearance; aging; training

THE BALANCE BETWEEN energy intake and energy expenditure regulates body energy reserves. Energy intake as well as energy expenditure decline with advancing age (13). The age-related decrease in "energy flux" is associated with an increased prevalence of lifestyle-related diseases (e.g., obesity, hypertension, etc.). Physical activity is frequently prescribed for older individuals as a means to stabilize body weight, enhance functional independence, and reduce cardiovascular risk. However, its influence on resting energy metabolism and sympathetic nervous system activity (SNSA) are unclear.

Resting metabolic rate (RMR) alone accounts for 60–80\% of daily energy expenditure (13). Physical activity is the most variable component of total energy expenditure and represents a significant stimulus to enhance total energy expenditure. Recent studies have suggested an influence of physical activity on RMR and SNSA. We recently reported that endurance-trained older men have higher rates of resting energy expenditure and norepinephrine (NE) appearance (15, 16) when compared with inactive older men. These findings suggest that older men who maintain a physically active lifestyle have increased resting energy requirements and heightened resting SNSA. It remains to be determined, however, whether introduction of physical activity to a previously inactive older population increases metabolic rate and alters resting sympathetic tone.

Therefore the first purpose of this study was to examine the effects of endurance training on RMR and plasma NE kinetics in older individuals. The second purpose was to examine potential modulators of RMR in response to endurance training by considering the contribution of changes in NE kinetics, body composition, food intake, and plasma hormones and substrates in healthy older individuals.

MATERIALS AND METHODS

Subjects. Nineteen older individuals (13 males and 6 females) in excellent general health participated in these studies. Criteria for subject selection were as follows: no clinical symptoms or signs of heart disease, resting blood pressure <140/90, normal resting electrocardiogram (ECG), a normal ECG response to an exercise stress test, absence of any prescription or over-the-counter medication that could affect cardiovascular function, no family medical history of diabetes or obesity, and weight stability (±2 kg) by medical history within the past year. At the time of the study, no individual was participating in a formal exercise program. Average daily energy expenditure as estimated from a leisure time physical activity questionnaire was 226 ± 37 kcal/day (26). The nature, purpose, and possible risks of the study were carefully explained to each subject before giving consent to participate. The experimental protocol was approved by the Committee on Human Research for the Medical Sciences of the University of Vermont.

Exercise program. The experimental treatment consisted of cycling exercise three times per week for 8 wk. The training sessions consisted of 10 min of flexibility exercises followed by cycling at an individually prescribed duration and intensity to expend a given number of calories. Exercise prescriptions were derived from the linear relation between heart rate and O2 consumption (V\textsubscript{O2}) established for each individual during a cycle ergometer test for maximal aerobic power. From this test,
a net energy expenditure (total cost of exercise minus RMR) was calculated. The exercise program was conducted under close supervision by an exercise physiologist and two research assistants, who monitored heart rate every 5 min to ensure adherence to the exercise prescription.

All volunteers initially began the first week with an exercise prescription designed to generate a net expenditure of 150 kcal at 60% of the maximal \( \text{Vo}_2 \) (\( \text{Vo}_{2,\text{max}} \)). Thereafter, the duration and intensity of the exercise program was incrementally increased, so that by the eighth week all volunteers were exercising at 85% of their \( \text{Vo}_{2,\text{max}} \) and expending a net energy expenditure of 300 kcal per exercise session. No injuries or health disorders were noted during the exercise program, and no modification in the protocol had to be introduced. Attendance at the exercise program was >95%. Exercise prescriptions were adjusted during the fourth week of the program to take into account increases in maximal aerobic power to maintain appropriate exercise intensity. The goal of the exercise program was to increase cardiovascular fitness and maintain volunteers in energy balance, so as to prevent the confounding influence of large changes in body weight and composition on RMR and NE kinetics (11). To ensure this objective, subjects were weighed at every exercise session and advised that the goal of the program was to maintain body weight and to avoid dietary restriction. In two subjects, a weight loss approaching 2 kg was noted during the fourth week of endurance training. These volunteers received dietary advice to increase food intake, and body weight was regained within 2 wk.

**Metabolic measurements.** All metabolic measurements and their reproducibility in our laboratory have been previously described in detail (15, 16). All measurements were performed 36 h after the last exercise session, since this time period has been shown to eliminate the residual effects of the last exercise bout on RMR and plasma NE (14). All volunteers followed an identical test sequence in the morning in which measurement of RMR and NE kinetics was established for each subject by indirect calorimetry for 45 min with the ventilated hood technique. Energy expenditure was calculated from the Weir equation (29).

Body fat was estimated from body density before and after exercise training by underwater weighing, with simultaneous measurement of residual lung volume by helium dilution using the Siri equation (24). Fat-free weight (FFW) was estimated as total body weight minus fat weight.

\( \text{Vo}_{2,\text{max}} \) was assessed by a progressive continuous test to exhaustion on a cycle ergometer, using an open-circuit gas analysis system. The initial workload for female and male subjects at 50 revolutions/min (rpm) was 25 and 50 W, respectively, for the first 3 min and was increased by 25 W every 2 min until exhaustion or until subjects were unable to maintain 50 rpm. All subjects reached their age-predicted maximal heart rate (pre, 160 ± 16 vs. post, 161 ± 17 beats/min) and a maximal respiratory quotient (RQ) greater than unity (pre, 1.12 ± 0.06 vs. post, 1.13 ± 0.05) before and after exercise training. \( \text{Vo}_{2,\text{max}} \) was considered the highest \( \text{Vo}_2 \) recorded during the test for successive minute intervals.

Energy intake before the exercise program and during the last week of the exercise program was recorded for 3 days, including two week days and one weekend day, as previously described (17). We examined the relation between self-recorded intake and covertly monitored food intake in seven individuals who lived at the Clinical Research Center for 10 days before beginning the exercise program. Mean energy intake, as estimated from 3-day food diaries (2,386 ± 69 kcal/day), was similar to covertly monitored intake in an in-patient setting (2,377 ± 49 kcal/day). This finding suggests that the self-recording of intake was representative of typical eating patterns in compliant subjects.

Plasma NE kinetics (appearance and clearance rates) were performed under steady-state conditions using a modification of the tritiated isotope dilution method (Esler et al. (3) and as previously described (15). The dose of the infused [\(^3\)H]NE was 0.71 μCi/min for 60 min. Arterialized blood samples were drawn at 50, 55, and 60 min later for determination of steady-state conditions, measurement of plasma NE, and calculation of plasma NE appearance and clearance rates. NE plasma clearance rates (l/min) were calculated as infusion rate [counts per minute (cpm)/min] divided by cpm per liter of plasma (mean of 3 samples corrected for extraction recovery). Appearance rates (μg/min) were calculated as clearance (l/min) × plasma NE concentration (μg/l). To examine the reproducibility of NE kinetics, test-retest conditions were performed in six individuals ~6 mo apart. No significant change in body weight or composition (±2 kg) occurred in these individuals. The coefficient of variation values for repeat determinations of NE concentrations, rates of NE appearance, and NE clearance are 16.9, 13.9, and 2.1%, respectively. Because two individuals refused to undergo NE kinetic experiments and because of technical problems with one individual, data for 16 individuals are available for analysis pre- and posttraining. Supine blood pressure was automatically measured (Dinamap; Critikon, Tampa, FL). No differences were noted for sodium intake before and after exercise training [pre, 3,362 ± 653 vs. post, 3,609 ± 832 (SD) mg/day].

Plasma glucose was determined using a YSI glucose analyzer (Yellow Springs Instruments, Yellow Springs, OH). Plasma immunoreactive insulin was determined by modification of the radioimmunoassay technique of Starr et al. (25). Plasma thyroxine (T\(_4\)) and free T\(_3\) and 3,5,3'-triiodothyronine (T\(_3\)) concentrations were measured using clinical assay kits (Baxter, Cambridge, MA), and free T\(_3\) was measured using an analogue assay (Diagnostic Products, Los Angeles, CA).

**Statistical analysis.** A Student’s \( t \) test for paired observations was used to examine the effect of exercise training on all dependent variables. A repeated-measures analysis of variance tested for steady-state concentrations and for the effects of endurance training on plasma concentrations of NE and [\(^3\)H]NE. Pearson product mo-
RESULTS

Physical characteristics. Subject characteristics before and after the exercise training program are presented in Table 1. By design, no significant changes were noted in body weight or composition. The range of changes in body weight (pre- to postmeasurement) during the training program were -0.2 to 0.2 kg. As expected, a significant increase in VO_{2max} was observed (P < 0.01), expressed in liters of O_2 or milliliters of O_2 per kilogram body weight. Supine systolic blood pressure showed a tendency to decline (P < 0.09), whereas supine diastolic pressure was lower (P < 0.05) after training.

RMR. The effects of exercise training on RMR and RQ are shown in Table 2. We noted a higher RMR in 19 of 19 volunteers measured 36 h after the last exercise bout regardless of how the data are indexed (Table 2). That is, an increase in RMR expressed as milliliters of O_2 or milliliters of O_2 per kilogram body weight. Supine systolic blood pressure showed a tendency to decline (P < 0.09), whereas supine diastolic pressure was lower (P < 0.05) after training. No effect of endurance training was noted on fasting RQ.

NE kinetics. The effects of exercise training on plasma NE concentrations and tracer are shown in Fig. 1. Because the model for calculation of NE kinetics is based on achievement of tracer equilibrium in plasma, we tested for stability of the tracer and NE concentrations over time. No significant time effect (50, 55, and 60 min postinfusion) was found in the tracer (cpm/ml) or in arterialized plasma NE, supporting the achievement of steady-state conditions before and after training. A significant treatment effect of exercise training was found for arterialized plasma NE but not for [3H]NE. This indicates that plasma levels of NE were higher after exercise training at 50, 55, and 60 min (P < 0.01), but no significant differences were noted in tracer concentrations at 50, 55, and 60 min.

Resting levels of plasma NE, NE appearance, and NE clearance are shown in Fig. 2. Baseline plasma NE levels are somewhat lower than previous studies (22). This probably reflects the excellent general health of our older population and the care taken to habituate subjects to the testing conditions. Fasting levels of arterialized plasma NE were 24% higher (P < 0.01) after training (256 ± 23 pg/ml) compared with before training (207 ± 17 pg/ml). This was primarily due to a 21% increase (P < 0.01) in the rate of NE appearance into the circulation in 14 of 16 volunteers (pre, 0.43 ± 0.04 vs. post, 0.52 ± 0.06 µg/min) and no significant changes in the rate of NE clearance (pre, 2.1 ± 0.07 vs. post, 2.1 ± 0.06 l/min).

Energy intake. Energy intake increased in 18 of 19 individuals as estimated from food diaries. Before endurance training, estimated intake was 2,305 ± 126 kcal/day and increased to 2,585 ± 117 kcal/day (P < 0.01). No modifications were noted in percent intake of macronutrients before exercise training and during the last week of the exercise program (%protein, 16 ± 1 vs. 17 ± 1; %carbohydrate, 48 ± 1.1 vs. 49 ± 2; and %fat, 31 ± 2 vs. 30 ± 2; not shown in table form).

Plasma hormones. Fasting plasma levels of hormones and substrates are shown in Table 3. A significant decrease was noted in plasma glucose (P < 0.01) and free T_3 (P < 0.01) after exercise training. No changes were noted in fasting levels of insulin, total T_3, total T_4, and free T_4.

Univariate analysis. As shown in Fig. 3, changes in RMR were significantly related to changes in the rate of NE appearance into circulation (r = 0.57; P < 0.02; n = 19). Changes in RMR were related to an increase in energy intake (kcal/day; r = 0.56; P < 0.02; n = 19) but not significantly to alterations in VO_{2max} expressed in liters per minute (r = 0.08) or per kilogram of body weight (r = 0.24). No significant relation was found between changes in RMR with alterations in fat weight (r = −0.23) or FFW (r = −0.24). No significant relation was noted between changes in RMR and plasma concentrations of thyroid hormones. Changes in NE appearance were not related to alterations in supine systolic (r = 0.09) or diastolic (r = −0.17) blood pressure. No significant relation was found between changes in NE appearance rate and percent intake of the macronutrients.

Multivariate analysis. Stepwise regression analysis was used to predict changes in RMR in response to exercise training. Potential predictors of RMR were changes in body weight, body fat, FFW, VO_{2max} (l/min), total and free T_3, energy intake, and NE appearance rate. Two independent variables together accounted for 49% (r^2) of the change in RMR; changes in energy intake alone

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**TABLE 1. Physical characteristics of 19 older individuals before and after an 8-wk exercise training program**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Exercise Training</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
</tr>
<tr>
<td>Age, yr</td>
<td>64.0±1.6</td>
</tr>
<tr>
<td>Height, m</td>
<td>1.7±0.02</td>
</tr>
<tr>
<td>Weight, kg</td>
<td>74.0±2.3</td>
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<tr>
<td>Body mass index, wt/ht^2</td>
<td>25.0±0.7</td>
</tr>
<tr>
<td>%Body fat</td>
<td>25.1±1.8</td>
</tr>
<tr>
<td>Fat free weight, kg</td>
<td>55.6±2.4</td>
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<tr>
<td>Fat weight, kg</td>
<td>18.4±1.2</td>
</tr>
<tr>
<td>VO_{2max}, ml·kg^-1·min^-1</td>
<td>2.2±0.1</td>
</tr>
<tr>
<td>Supine systolic BP, mmHg</td>
<td>129±4</td>
</tr>
<tr>
<td>Supine diastolic BP, mmHg</td>
<td>77±3</td>
</tr>
</tbody>
</table>

Values are means ± SE. VO_{2max}, maximal O_2 consumption; BP, blood pressure. * P < 0.05; † P < 0.01.

**TABLE 2. Resting metabolic rate before and after an 8-wk exercise training program in 19 older individuals**

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Exercise Training</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
</tr>
<tr>
<td>RMR, ml O_2/min</td>
<td>197±8±6.2</td>
</tr>
<tr>
<td>RMR, kcal/min</td>
<td>0.97±0.03</td>
</tr>
<tr>
<td>RMR, kcal·kg FFW^-1·min^-1</td>
<td>0.017±0.0003</td>
</tr>
<tr>
<td>Respiratory quotient</td>
<td>0.86±0.01</td>
</tr>
</tbody>
</table>

Values are means ± SE. RMR, resting metabolic rate; FFW, fat-free weight. * P < 0.01.
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FIG. 1. Bars are means ± SE. Plasma concentrations of norepinephrine (NE) and arterialized plasma [3H]NE before and after endurance training. Plasma concentrations of NE were significantly higher at 50, 55, and 60 min after endurance training (P < 0.01), whereas no differences were found for arterIALIZED plasma [3H]NE.

FIG. 2. Bars are means ± SE. Resting levels of plasma NE, NE clearance, and NE appearance before and after endurance training. Plasma levels of NE concentration and specific activity represent mean values of 50-, 55-, and 60-min samples depicted in Fig. 1. Plasma concentrations of plasma NE and NE appearance were significantly higher (P < 0.01) after endurance training, whereas no changes were noted in NE clearance.

FIG. 3. Changes in resting metabolic rate (RMR) with changes in rate of NE appearance into circulation. Data for 3 subjects are missing due to fact that 2 subjects were unwilling to participate in infusion experiments and due to technical problems with 1 volunteer.

DISCUSSION

The major purpose of this study was to examine the influence of endurance training on RMR and SNSA in older persons. The new findings are: 1) endurance training increases RMR and resting levels of NE appearance into the circulation in healthy older individuals, and 2) approximately one-half of the increase in RMR can be accounted for by an increase in food intake and by the rate of NE appearance into the circulation.

Endurance training and RMR. The influence of endurance training on RMR has been frequently examined in

TABLE 3. Plasma hormones and substrates of 19 older individuals before and after an 8-wk exercise training program

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Exercise Training</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Before</td>
</tr>
<tr>
<td>Insulin, pmol/l</td>
<td>78.6±8.9</td>
</tr>
<tr>
<td>Glucose, mmol/l</td>
<td>5.8±0.1</td>
</tr>
<tr>
<td>Total T3, nmol/l</td>
<td>1.43±0.05</td>
</tr>
<tr>
<td>Free T3, pmol/l</td>
<td>2.70±1.1</td>
</tr>
<tr>
<td>Total T4, nmol/l</td>
<td>95.9±3.9</td>
</tr>
<tr>
<td>Free T4, pmol/l</td>
<td>16.0±0.6</td>
</tr>
</tbody>
</table>

Values are means ± SE. T3, 3,5,3'-triiodothyronine; T4, thyroxine.

* P < 0.01.

accounted for 32% (r = 0.57; r^2 = 0.32; P < 0.05) of the variation for change in RMR, and the rate of NE appearance accounted for an additional 17% (r = 0.70; r^2 = 0.49; P < 0.05). No independent contribution of the other variables to the model was noted.

Because males and females were studied in the same protocol, we examined the possibility of sexual dimorphism in response to exercise with respect to metabolic and sympathetic nervous system indicators. We found no differences in the changes between males and females with respect to V̇O_2̇_max (0.29 ± 0.07 vs. 0.39 ± 0.06 l/min), RMR (0.08 ± 0.001 vs. 0.11 ± 0.002 kcal/min), plasma NE (47 ± 14 vs. 54 ± 17 pg/ml), NE appearance (0.10 ± 0.04 vs. 0.08 ± 0.03 µg/min), and NE clearance (−0.05 ± 0.05 vs. 0.03 ± 0.11 l/min; not shown in table form).
younger individuals. Some investigators, but not all (20), have found higher RMR values in endurance-trained individuals (18, 19, 27) or in previously inactive individuals after exercise training (6, 7, 26). Previous cross-sectional studies have shown that RMR is higher in physically active older men than in untrained older men (16). To our knowledge, only one other study has examined the influence of endurance training on RMR in older individuals, and they did not find a training effect on RMR (9). Perhaps the fact that volunteers trained at a greater exercise intensity in this study compared with the training program of Meredith et al. (9) may have contributed to the observed higher RMR, because higher training intensities have been shown to enhance RMR (7). In the present study, the 10% increase in RMR extrapolated to a 24-h basis would account for an additional 144 kcal expenditure per day, which is ~6% of the energy intake for these older persons.

The increase in RMR may play a role in permitting older individuals to consume more calories without a concomitant increase in body fat. We noted a 12% increase in estimated energy intake without marked changes in energy expenditure in response to training. Both energy intake and physical activity decline with advancing age (8). This decrease in energy flux (e.g., intake and expenditure) is associated with an increase in body fat and a loss of muscle mass. This suggests that the relative decline in total energy expenditure (RMR, physical activity, etc.) is proportionally greater than the decline in energy intake. An increase in physical activity may represent a relevant clinical intervention to stimulate energy flux by stimulating food intake and energy expenditure in older persons and possibly restoring energy balance. It should be noted, however, that the use of exercise as a means to increase energy expenditure and energy intake may have greater relevance for the healthy ambulatory older population than the hospitalized segment of the elderly with chronic disease.

Endurance training and NE kinetics. The majority of studies that have examined the effects of endurance training on SNSA have been performed in younger normotensive individuals. Furthermore, they have used plasma levels of NE as an index of SNSA. Some investigators have found no training effect on resting plasma NE (12), whereas others have found lower (1) and higher plasma concentrations of NE after training (10). These divergent results probably reflect the heterogeneity of the population studied, the differences in degree over dietary control before the determination of plasma NE, and the state of energy balance of the volunteers.

We have used infusions of tracer-labeled NE to estimate rates of NE appearance and clearance as indexes of SNSA in response to endurance training, since it permits the estimation in vivo of two concurrent processes, appearance (or spillover) of NE into plasma after release from sympathetic nerve endings and subsequent removal of NE from the circulation. In our previous cross-sectional study, we found higher rates of NE appearance in physically active older men relative to untrained men, suggesting that endurance training enhances resting SNSA in older individuals (15). We extend this work by investigating changes in NE kinetics in older individuals in response to endurance training. This experimental approach avoids the pitfall that the relation between endurance training and SNSA may be due to other covariates, such as the genotype (2). The results of this study support our cross-sectional work (15) and collectively show that endurance training increases NE appearance rate at rest in normotensive older persons. In the present work, 14 of the 16 subjects increased NE appearance rate in response to endurance training (Fig. 2). Furthermore, a reduction in fasting blood pressure was noted that was unrelated to changes in NE kinetics. This finding confirms previous reports regarding the blood pressure lowering effects of regular training but the absence of an association between temporal changes in blood pressure and plasma NE or NE kinetics in normotensive individuals (5).

To our knowledge, only two other studies have examined the effects of endurance training on NE kinetics, and these were performed on younger individuals (5, 23). In a 4-wk daily endurance training program, Jennings et al. (5) found large variation with some subjects showing a reduction, whereas others increased NE appearance rate. Dietary intake was not controlled, and body fat was not assessed in this study. Schwartz et al. (23) found no changes in NE appearance rate in 18 moderately obese younger males who lost a moderate amount of body weight (2.2 kg) and body fat during a 3-mo endurance training program. It is possible that these subjects were adapted to a lower energy state in this study, which may have confounded any effect of endurance training on SNSA. Neither of the aforementioned studies examined older individuals, whose SNSA response to endurance training may be quantitatively different than younger individuals.

Because changes in NE appearance were not significantly related to changes in VO\(_{2\text{max}}\) \((r = 0.14)\), this suggests that factors other than an increase in cardiovascular fitness may influence NE appearance rate. A possible explanation for the higher rate of NE appearance after training may relate to the increase in energy intake that accompanied the increase in physical activity. Increased energy intake has been shown to be a potent stimulator of SNSA in humans (21, 22).

Preliminary evidence from this study provides indirect support for the involvement of a sympathetic and dietary component in mediating changes in RMR in response to exercise training. This concept is supported by the findings that approximately one-half of the increase in RMR was related to increases in NE appearance rate and to an increase in calories consumed, whereas changes in body composition, plasma thyroid hormones, and VO\(_{2\text{max}}\) contributed little to variation in RMR in response to training. The sympathetic contribution to variation in RMR has been an area of controversy. Some investigators have suggested that variability in RMR may be due to a facultative component of sympathoadrenal origin (30). However, to our knowledge, this is the first study to examine the contribution of NE kinetics to changes in RMR in response to a closely supervised endurance training, in which energy intake and body weight were carefully monitored.

We have paid close attention to several other meth-
odological considerations that may confound interpretation of experimental designs involving SNSA and exercise training. Volunteers were maintained in stable body weight to avoid the confounding influence of alterations in energy balance and its influence on SNSA (11) during exercise training. Dietary advice was available to assist subjects in maintaining stable body weight and sodium intake. Second, metabolic rate and NE kinetics were measured 36 h after the last exercise bout, because we have shown that vigorous exercise does not influence RMR and plasma NE after this time period (14). Lastly, volunteers were habituated to all experimental procedures before testing and spent the evening before all measurements at the Clinical Research Center where they fasted for 12 h.

Several limitations of our results should be borne in mind. First, the isotope dilution method of NE kinetics is an overall estimate of sympathetic nervous tone. It is now quite clear that specific response patterns occur within the cardiovascular system, with nonuniform engagement of target organs and tissues (4). Thus the source of the increase in NE appearance in response to endurance training cannot be identified. Furthermore, the use of food intake diaries to estimate changes in food intake in response to endurance exercise may be questioned with respect to their accuracy and precludes the conclusion that older individuals “spontaneously” increased food intake in response to endurance training.

From the results of the present study, we hypothesize that RMR and SNSA are higher in older individuals that have higher rates of energy flux. An increase in energy flux occurs by proportionally matching an increase in energy expenditure (by exercise) to an increase in food intake. Furthermore, the increase in food intake may stimulate resting SNSA. Collectively, it appears that RMR and SNSA respond not only to states of energy imbalance but to the flow of energy through the organism when individuals are in energy balance.

In conclusion, endurance training increases RMR in older individuals. This increase is at least partially influenced by an increased rate of NE appearance and food intake. Endurance training provides a suitable intervention to enhance resting energy requirements in older individuals.

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