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Resistance Training and Energy Balance

Eric T. Poehlman and Christopher Melby

In this brief review we examine the effects of resistance training on energy expenditure. The components of daily energy expenditure are described, and methods of measuring daily energy expenditure are discussed. Cross-sectional and exercise intervention studies are examined with respect to their effects on resting metabolic rate, physical activity energy expenditure, postexercise oxygen consumption, and substrate oxidation in younger and older individuals. Evidence is presented to suggest that although resistance training may elevate resting metabolic rate, it does not substantially enhance daily energy expenditure in free-living individuals. Several studies indicate that intense resistance exercise increases postexercise oxygen consumption and shifts substrate oxidation toward a greater reliance on fat oxidation. Preliminary evidence suggests that although resistance training increases muscular strength and endurance, its effects on energy balance and regulation of body weight appear to be primarily mediated by its effects on body composition (e.g., increasing fat-free mass) rather than by the direct energy costs of the resistance exercise.

Key Words: weight training, nutrition, caloric expenditure, body composition

This review focuses on recent studies that have advanced our understanding regarding the influence of resistance training on energy balance. Specifically, we consider the effects of resistance training on energy expenditure and substrate oxidation. Exercise is often prescribed to increase daily energy expenditure and fat oxidation to maintain proper levels of body weight and composition. Recent evidence suggests that resistance training may influence the long-term control of body weight and composition and alter substrate oxidation. We will briefly examine the effects of resistance training on total daily energy expenditure, its components, and substrate oxidation. It is not our intent to review the effects of resistance or endurance exercise on muscle hypertrophy, strength, insulin resistance, or cardiovascular risk.

Components of Daily Energy Expenditure

Resting Metabolic Rate

Resting metabolic rate (RMR) represents the largest portion of daily energy expenditure (60 to 75%) and is a measurement of the energy expended to maintain normal

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body functions and homeostasis (Figure 1). Theoretically, small perturbations in RMR would significantly impact the regulation of body weight. Processes that regulate body weight include the energetic cost of resting cardiovascular and pulmonary functions, the energy consumed by the central nervous system, maintenance of cellular homeostasis, and other biochemical reactions involved in maintaining resting metabolism.

The RMR is primarily related to the amount of fat-free mass in the body and is also influenced by age, gender, body composition, and genetic factors. For example, it is well known that the RMR decreases with advancing age (2 to 3% per decade) (21, 41), and this decrease is primarily attributed to the loss of fat-free mass. Males tend to have a higher RMR than females because of their greater body size. Moreover, a low RMR (for an individual's body size) is a predictor of weight gain over time (27). The dependency of RMR on body composition must be considered when individuals of different age, sex, and physical activity status are compared. Other processes, such as sympathetic nervous system activity, thyroid hormone activity, and sodium–potassium pump activity, have been shown to contribute to the variation in RMR among individuals. A more detailed examination of age and exercise effects on RMR can be found in previous reviews (21, 24).

The Thermic Effect of Feeding

The thermic effect of feeding (TEF) is the increase in energy expenditure associated with food ingestion. The TEF represents approximately 10% of daily energy expenditure and includes the energy costs of food absorption, metabolism, and storage

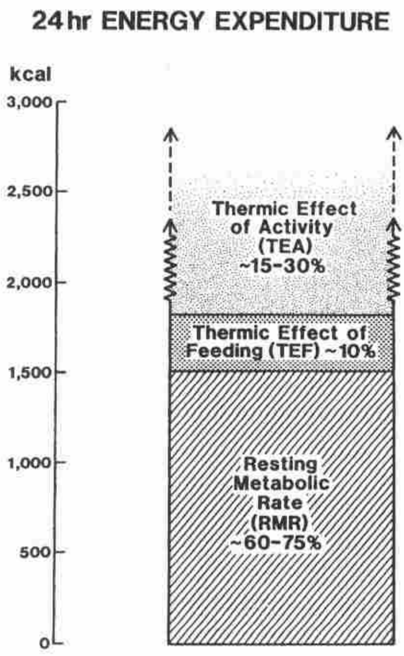

Figure 1 — The components of 24-hr energy expenditure.

(Figure 1). The magnitude of the TEF depends on several factors, including caloric content and composition of a meal as well as the individual's antecedent diet. Following meal ingestion, energy expenditure increases for 4 to 8 hr, its magnitude and duration depending on the quantity and type of macronutrient (i.e., protein, fat, or carbohydrate).

The TEF has been divided into subcomponents: obligatory and facultative thermogenesis. The obligatory component is the energy cost associated with absorption and transport of nutrients and the synthesis and storage of protein, fat, and carbohydrate. The "excess" energy expended above the obligatory thermogenesis is the facultative thermogenesis, which is thought to be partially mediated by sympathetic nervous system activity. The TEF has also been shown to decrease with advancing age and may be associated with the development of insulin resistance (21). We found no studies, however, in which the effects of resistance training on TEF were examined.

The Thermic Effect of Physical Activity

The most variable component of daily energy expenditure is the thermic effect of physical activity. This component includes the energy expended above the resting metabolic rate and the thermic effect of feeding, which includes the energy expended through voluntary exercise and the energy devoted to involuntary activity such as shivering, fidgeting, and postural control. In sedentary individuals, the thermic effect of activity may comprise as little as 100 kcal per day; in highly active individuals it may approach 3,000 kcal per day. Thus, physical activity is a significant factor governing the daily energy expenditure in humans because it is extremely variable and subject to voluntary control. Physical activity tends to decrease with advancing age, which may lead to a loss of fat-free mass and an increase in adiposity (13, 25). Males tend to expend more calories through physical activity than females, due partially to the greater energy cost of moving a larger body mass. The effects of resistance training on physical activity in free-living individuals are understudied and represent an important new area of research.

Resting metabolic rate, thermic effect of a meal, and physical activity often overlap. Although there are daily variations in energy balance, placing individuals in a slight energy deficit or surplus, maintenance of a stable body weight depends on a long-term balance of energy intake and energy expenditure. It is unclear how behavioral and physiological/metabolic characteristics are regulated to allow a balance of energy intake with energy expenditure.

Measurement Issues

Many methods of measuring energy expenditure have become available over the years, and they vary in complexity, cost, and accuracy. The techniques that have been used to measure total daily energy expenditure and its components will be briefly described. A more detailed explanation of the laboratory methods to measure energy expenditure was published previously (19).

Indirect Calorimetry

Indirect calorimetry involves estimating energy production by measuring oxygen consumption and carbon dioxide production rather than by directly measuring heat transfer. This method requires that a steady state of carbon dioxide production and respiratory exchange be reached and that subjects have a normal acid-base balance. To determine the RMR, measurements are usually taken with the subject in a supine or semireclining position after a 10- to 12-hr fast. Depending on the equipment, the subject typically breathes through a mouthpiece, face mask, or ventilated hood or is placed in a room calorimeter in which expired gases are collected. Typical RMR values range from 0.7 to 1.6 kcal/min, depending on the subject's body size, body composition, level of physical training, and gender. The room where the measurements are conducted is usually darkened and quiet, and the subject remains undisturbed during the measurement process. RMR measurement typically lasts 30 min to 1 hr, whereas postprandial measurements frequently take 3 to 8 hr. These measurements are generally reproducible (with a coefficient of variation of less than 5%).

Several methods have been used to measure oxygen consumption and carbon dioxide production at rest. Generally, an "open circuit" method is used in which both ends of the system are open to atmospheric pressure, and the subject's inspired air and expired air are kept separate by means of a three-way respiratory valve or nonrebreathing mask. The expired gases are usually collected in a Douglas bag or Tissot respirometer for the measurement of oxygen and carbon dioxide content. Subjects who are not accustomed to using a mouthpiece may hyperventilate, which may result in inappropriately high levels of oxygen consumption and carbon dioxide production. When a mask is used, it is frequently difficult to obtain an airtight seal around the subject's nose and mouth.

To circumvent some of these problems, ventilated hoods have been developed. The subject is fitted with a transparent hood equipped with a snugly fitting collar; fresh air is drawn into the hood via an intake port, and expired air is drawn out of the hood by a motorized fan. The flow rate is measured by a pneumotachograph, and aliquots of the outflowing air are analyzed for oxygen consumption and carbon dioxide production after temperature and water vapor content have been adjusted. Oxygen consumption and carbon dioxide production are calculated from the differences in their concentrations in the inflowing and outflowing air and the flow rate. Ventilated hoods are excellent for both short- and long-term measurements but are less useful in measuring the energy expenditure of physical activity; in the latter case the subject may find the hood uncomfortable, and there is a problem with the dissipation of perspiration and water vapor.

Physical Activity

Measuring energy expenditure resulting from physical activity has traditionally presented several methodological challenges. Indirect calorimetry (using a mouthpiece or face mask) has been used to assess oxygen consumption and carbon dioxide production. This method generally yields reliable and accurate measurements of the energy cost of physical activity in a laboratory setting but provides no information about the energy cost of physical activity under free-living conditions because of the stationary nature of the equipment. Portable respirometers employ a face mask with valves that direct expired air through collection tubes to a respirometer carried on the subject's back. The respirometer contains a flowmeter and a sampling device that collects an aliquot of expired gases for analysis at a later time. There are drawbacks to this method: There is an inherent delay in obtaining results, and the rate of energy expended during the period of work performance is integrated over the entire period of gas collection.

In an attempt to avoid some of the problems associated with measuring free-living physical activity, several less complicated (and less accurate) methods have been devised. These methods employ physiological measurements, observation, and records of physical activity, as well as activity diaries or recall. Heart rate recording, used to measure energy expenditure, is based on the correlation between heart rate and oxygen consumption during moderate to heavy exercise. The correlation, however, is much poorer at lower levels of physical activity, and a subject's heart rate may be altered by such events as anxiety or change in posture without significant changes in oxygen consumption.

It is possible to estimate energy expenditure over relatively long periods by measuring energy intake and changes in body composition. However, there are errors inherent in attempting to accurately determine energy intake over several days, weeks, or months, and there are errors inherent in the methods available for determining body composition.

Time-motion studies have been used to estimate the energy expenditure of physical activity in real-life situations. In time–motion studies, an observer keeps detailed records of physical activity, and energy expenditure is estimated from the duration and intensity of the work performed. The major problem with this method is the marked individual variations in the energy cost of performing a particular task.

Physical activity diaries and physical activity recall instruments have been used to quantify the energy costs of different activities over a representative period of time. Record keeping is often inaccurate and may interfere with the subject's normal activities. Furthermore, the subject's recall of physical activity depends on his or her memory, which may not always be reliable. Measuring motion by devices such as a pedometer or an accelerometer may provide an index of physical activity (i.e., counts) but does not measure energy expenditure. In summary, the measurement of free-living physical activity continues to be the most significant challenge in the field of energy metabolism.

In recent years, large respiration chambers have been built in laboratories. Such a chamber operates on the same principal as the ventilated hood system: It is essentially a large, airtight room in which temperature and humidity are controlled. Fresh air is drawn into the chamber and allowed to mix. Simultaneously, air is drawn from the chamber, and the flow rate is measured and analyzed continuously for oxygen and carbon dioxide content. The size of the room affords the subject sufficient mobility to sleep, eat, exercise, and perform normal daily routines, making detailed measurements of energy expenditure possible over several hours or several days. Room calorimeters are probably the best method available for conducting short-term studies (several days) of energy expenditure in humans when the object is to measure RMR, the thermic effect of a meal, and the energy expenditure of physical activity. Physical activity level is quantified by a radar system that is activated by the subject's movement within the chamber. As with other movement devices, the radar system does not quantify the intensity of activity. It is also likely, however, that free-living physical activity is blunted in the room calorimeter because of its confining nature. Thus, room calorimeters do not offer the best model for accurately quantifying free-living physical activity and total energy expenditure. Although room calorimeters are moderately expensive to construct, they provide reliable information on daily energy expenditure and substrate oxidation under well-controlled conditions.

Doubly Labeled Water

The doubly labeled water technique is used to determine energy requirements in free-living populations and in subjects for whom traditional measures of energy expenditure are impractical and difficult (e.g., infants and critically ill patients). The basis of this technique is that after the individual consumes a bolus dose of two stable isotopes of water (^2H_2O and $H_2{}^{18}O$), ^2H_2O is lost from the body in water alone, whereas $H_2{}^{18}O$ is lost not only in water but also as $C^{18}O_2$ via the carbonic anhydrase system (31). The difference in the two turnover rates is therefore related to the carbon dioxide production rate, and energy expenditure can be calculated using this information plus knowledge of the fuel mixture oxidized (from the composition of the diet).

The doubly labeled water technique has several advantages: (a) It measures total daily energy expenditure, which includes an integrated measure of resting metabolic rate, the thermic response to feeding, and the energy expenditure of physical activity, (b) it permits an unbiased measurement of free-living energy expenditure, and (c) measurements are conducted over extended periods of time (1 to 3 weeks). Thus, energy values derived from the doubly labeled water method represent the typical daily energy expenditure and therefore the daily energy needs of free-living adults. Furthermore, this technique provides an accurate estimate of free-living physical activity. Daily free-living physical activity is calculated from the difference between the total daily energy expenditure and the combined energy expenditures of the RMR and the thermic effect of meals. Thus, doubly labeled water provides the most realistic estimate in free-living subjects of the average daily energy expenditure associated with physical activity and its response to resistance training.

A disadvantage of the doubly labeled water method is its expense and limited availability. Consequently, the technique does not lend itself to epidemiological studies or studies of large groups of subjects. However, this technique is now being used to examine energy requirements of persons in a variety of healthy and diseased states, as well as individuals' energetic adaptations to several modes of exercise training. Figure 2 shows typical changes in daily energy expenditure and its components in a younger and an older individual.

Cross-Sectional Studies of Resistance Training and Energy Expenditure

We will examine several cross-sectional studies that have compared energy expenditure in resistance-trained individuals with that in untrained persons. It is important to note that cross-sectional studies cannot provide information on the cause-and-effect relationship between resistance training and energy expenditure. Individuals who participate in resistance training may possess constitutional differences in energy expenditure that predispose them to train with weights. However, the significant differences in body composition between untrained individuals and those who have resistance trained for many years permit researchers to estimate the effects of resistance training on energy balance to an extent that may not be possible with

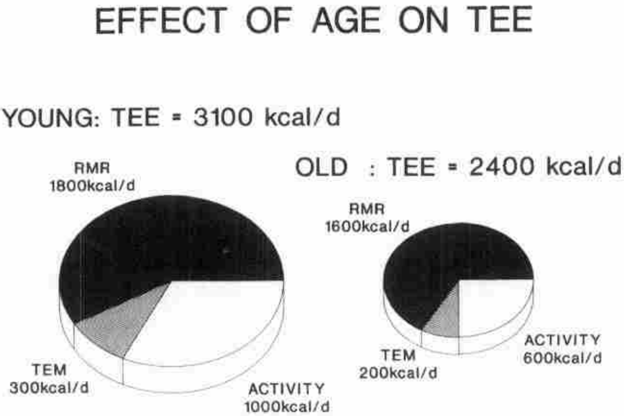

Figure 2 — The effect of age on total daily energy expenditure (TEE). RMR = resting metabolic rate; TEM = thermic effect of a meal.

typical short-term resistance training intervention studies. It should be noted, however, that exercise training studies are a more robust method of examining the effects, in terms of energy expenditure, of changes in body composition produced by resistance training.

Our group (22) examined RMR (normalized for differences in fat-free mass) in aerobic trained (n = 36), resistance trained (n = 18), and sedentary younger individuals (n = 42). Resting metabolic rate was 5% higher in resistance-trained men than in untrained men, whereas aerobic-trained individuals had a 10% higher RMR compared with untrained young men, respectively (Figure 3, right panel). These differences corresponded to a 187 and 86 kcal/day greater resting energy expenditure in aerobic- and resistance-trained young men, respectively. This study provided the first evidence of higher RMR in resistance-trained individuals relative to nonexercising controls. However, the energy expenditure in aerobic-trained individuals (for their metabolic size) is clearly the more striking finding.

In a similar study of younger women, Ballor and Poehlman (4) found no difference in RMR between resistance-trained (n = 13) and untrained (n = 48) younger women, whereas aerobic-trained (n = 21) women showed a 6% higher RMR compared with both groups. The absence of a higher RMR in resistance-trained women is divergent with the results of our previous study in men (22). It is unclear which factor or factors may account for the sex difference in the relationship between resistance training and RMR, although variation in training intensity and/or volume may be contributory. The resistance-trained men in the first study were engaging in a higher volume of resistance exercise than the women in the second study. Moreover, inherent differences between sexes with respect to anabolic hormones may be contributory.

Several researchers have examined energy expenditure in resistance-trained older individuals. In middle-aged men, Toth et al. (36) found no difference in RMR between 19 resistance-trained and 30 untrained volunteers. However, aerobic-trained middle-aged men (n = 37) had a higher RMR than untrained volunteers (86 kcal/day). In middle-aged women, RMR was 16% higher in resistance-trained volunteers than in untrained volunteers, but RMR was similar between resistance-trained

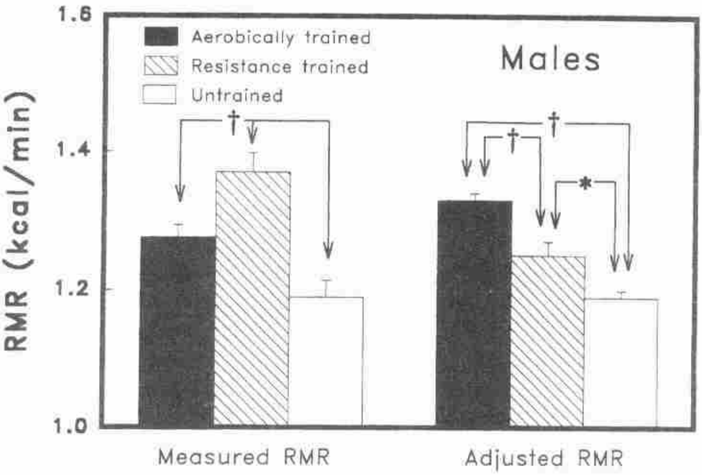

Figure 3 — Differences in resting metabolic rate (RMR) in aerobically trained, resistance trained, and untrained younger males. Adjusted RMR = values adjusted for differences in fat-free mass using analysis of covariance.

volunteers and the aerobic-trained group (37). The elevated RMR in the resistance- and aerobic-trained middle-aged women translated to a 160 and 150 kcal/day increase in daily resting energy requirements, respectively. This finding suggests that resistance training may blunt the age-related decline in RMR in women.

Bosselaers and coworkers (5) examined 24-hr energy expenditure in 10 resistance-trained subjects (9 men, 1 woman) and 10 healthy controls matched for age, sex, and percent body fat. They found a higher 24-hr energy expenditure in resistance-trained subjects compared to untrained controls (+354 kcal/day). This difference was eliminated after the researchers adjusted 24-hr expenditure for difference in fat-free mass. This finding suggests that the elevated energy expenditure in resistance-trained subjects is attributable to their greater quantity of fat-free mass. These results suggest that chronic resistance training may elevate RMR, although this association may be age- and sex-specific. However, the disparity in these cross-sectional studies and possible selection bias preclude firm conclusions regarding the effects of resistance training on energy expenditure.

Intervention Studies of Resistance Training and Resting Metabolic Rate

Several investigators have examined the effects of resistance exercise training programs on energy expenditure in younger and older individuals. These studies mainly have been confined to the examination of changes in RMR. This is understandable given that RMR is a large component of daily energy expenditure and measuring total daily energy expenditure by doubly labeled water is difficult and expensive. Theoretically, even small changes in RMR may significantly affect the regulation of body weight and body composition over extended periods of time.

Broeder et al. (6) found no change in RMR in 13 young male volunteers following 12 weeks of high-intensity training, despite a 2-kg increase in fat-free mass. Given the published regression equations in the literature, which show an increase in RMR of approximately 50 kcal per day for each kilogram of fat-free mass increase (1), it may seem surprising that no increase in RMR was found. However, the increase that accompanies resistance training is likely to result almost entirely from muscle hypertrophy. Of the constituents of fat-free mass, the contribution of skeletal muscle to RMR is considerably less than that of the internal organ mass, which is not likely to change much with resistance exercise.

Van Etten et al. (42) investigated changes in energy expenditure in 21 younger males after a 12-week weight training program. Sleeping metabolic rate was measured in a respiration chamber. Weight training increased fat-free mass (1.1 ± 1.3 kg) and decreased fat mass (2.3 ± 1.5 kg). The investigators did not find any change in sleeping metabolic rate. It is possible that if changes in RMR are mediated by changes in body composition in response to resistance training, the small changes in fat-free mass observed by Van Etten et al. were not sufficient to impact RMR.

Pratley and colleagues (26) examined changes in RMR following 16 weeks of resistance training in 13 older men. The use of resistance training in the elderly is particularly interesting because of the age-related decline in energy expenditure. RMR increased by approximately 8% or 120 kcal/day. Although fat-free mass increased during the training program (+1.6 kg), the increase in RMR persisted after the authors controlled for changes in fat-free mass. This finding suggests that the elevation in RMR was due to both the increased quantity and the metabolic activity of fat-free mass. The investigators speculated that the increase in RMR was related to the increase in plasma levels of norepinephrine. However, they could not rule out the possibility that the elevated RMR was due to the residual effect of the last bout of exercise, given that the RMR measurement was performed 22 to 24 hr following the last training session.

Campbell and coworkers (9) found a 6.8% increase in RMR in 12 elderly men and women following a 12-week resistance-training program. Fat-free mass increased following training (1.4 kg) due to an increase in total body water. Thus, changes in RMR were not attributable to alterations in respiring tissues. These findings suggest that resistance training stimulates RMR in older individuals through a mechanism that is independent of changes in fat-free mass. Furthermore, RMR was measured ~45 hr after the last training session. Thus, it is unlikely that the assessment of RMR was due to the residual effects from the last exercise bout.

Treuth et al. (40) found a 9% increase in RMR in 13 elderly women after a 16-week resistance training program. However, total daily energy expenditure as measured by a whole-room calorimetry was unchanged. Since there were no changes in fat-free mass during the training program, these results suggest that the increase in RMR was independent of increases in fat-free mass. Collectively, these studies suggest that resistance training stimulates RMR in older but not in younger individuals and that this effect is independent of changes in fat-free mass. However, changes in fat-free mass are frequently small and within the error of the measurement technique. Resistance training programs of long duration that result in large increases in fat-free mass may help resolve whether there is an increase in RMR above that which can be accounted for by changes in body composition.

Trueth et al. (39) compared the effects of a 16-week resistance training program with and without weight loss on fat-free mass and RMR in 15 postmenopausal women (50–69 years old). In women who underwent resistance training and weight loss, percent body fat decreased by 4%, with no significant change in fat-free mass.

When data from all women were combined (n = 15), the increase in RMR was statistically significant (50 kcal per day). These results suggest that resistance training may offset the decline in fat-free mass and RMR with advancing age.

Ballor et al. (3) examined whether resistance training would help subjects maintain body weight following weight loss by attenuating weight loss–induced reductions in RMR. Ballor and colleagues measured RMR and the thermic effect of a meal in a group of 18 older volunteers (55 to 70 years) who had recently lost a mean of 9 ± 1 kg. The weight loss program reduced RMR by approximately 260 kcal per day. Weight training during the 12-week program tended to increase RMR (72 kcal per day) and the thermic effect of a meal (16 kcal over a 5-hr postprandial measurement period) in individuals who lost weight. Collectively, resistance training restored approximately 34% (88 kcal) of the 260-kcal lower energy expenditure generated by the weight loss program.

The mechanisms underlying the increase in RMR observed following resistance training programs are unknown. It has been suggested that training-induced increases in protein turnover enhance energy expenditure given the substantial portion of RMR attributed to this process (44). However, Campbell et al. (9) noted that changes in protein turnover in their study increased RMR by only 1%. It is possible that the negative energy balance often associated with resistance training regimens limits the increase in protein turnover. However, since little or no change in body composition was noted in any of the aforementioned studies, it is unlikely that a negative energy balance, and therefore a suppression of protein synthesis, occurred. Thus, although increases in protein turnover may contribute to the increased RMR in response to resistance training, the effect appears to be small.

In our laboratory, we have shown that the increase in RMR following endurance training is associated with an increased rate of appearance of norepinephrine in the circulation (23). To investigate the possibility that changes in sympathetic nervous system activity are related to elevation in RMR in response to endurance training, Pratley and coworkers (26) measured plasma norepinephrine levels in response to 16 weeks of resistance training in 13 healthy older men. Although increases in both RMR (7.7%) and plasma norepinephrine (36%) were noted, changes in these variables were not correlated. Moreover, Ryan et al. (29) found no increase in plasma norepinephrine in response to 16 weeks of resistance training. The lack of association between changes in RMR and sympathetic nervous system activity may be because plasma norepinephrine concentrations are a crude estimate of global sympathetic tone. Therefore, it remains to be determined whether elevations in basal sympathetic nervous system contribute to the increased RMR observed in older individuals following resistance training.

In the above-mentioned studies, resistance training enhanced RMR only in those studies in which older individuals (>50 years) underwent exercise training. Pratley et al. (26) suggested that the lower RMR in older individuals relative to younger individuals may permit greater flexibility for change. However, because the major determinant of the decline in RMR with age is the concomitant decline in fat-free mass (41), elevations in RMR in response to resistance training in older individuals would most likely be attributable to increases in fat-free mass. That RMR increased in each of the above studies independent of changes in fat-free mass suggests that the stimulatory effect of resistance training on RMR in older individuals is not solely associated with the partial restoration of fat-free mass but must work through other, yet-undefined mechanisms.

When the scientific objective is to examine the effects of resistance training on energy balance, more meaningful information is gained by measuring total daily energy expenditure with doubly labeled water. Ultimately, the balance in total daily energy expenditure and energy intake regulates body weight and body composition. Thus, the use of doubly labeled water in combination with indirect calorimetry provides a more definitive assessment of the effects of resistance training on daily energy expenditure, free-living physical activity, and its relationship to changes in body composition. Accurately assessing free-living physical activity has been problematic in resistance training programs. This is unfortunate, since free-living physical activity is the most variable component of total daily energy expenditure and has significant potential to alter fat mass and fat-free mass. Moreover, a low level of physical activity is a significant predictor of increased body weight and central adiposity over time (13, 25). Resistance training may enhance free-living physical activity by several mechanisms: increased protein synthesis, increased sympathetic nervous system activity, and/or increased levels of fat-free mass.

Van Etten et al. studied 18 healthy, initially sedentary men (23 to 41 years) who underwent resistance training for 18 weeks (42, 43). In a subsample of 12 individuals, total daily energy expenditure was measured before and after the training period using doubly labeled water. Body composition was measured using a three-compartment model of body composition using underwater weight and total body water. The volunteers trained two times per week, performing three sets of 15 repetitions for the major muscle groups. After 18 weeks, volunteers lost 2.0 kg of fat mass and gained 2.1 kg of fat-free mass. The mean increase in daily energy expenditure after the 18-week training program approached 260 kcal per day, of which 40–50% was due to the direct caloric cost of the resistance training program. Sleeping metabolic rate and free-living physical activity (independent of the direct energy cost of the training program) did not change in response to resistance training. The absence of an increase in free-living physical activity was confirmed with measurements from a triaxial accelerometer. Thus, this well-controlled study does not support the hypothesis that resistance training, resulting in moderate changes in body composition, increases resting energy expenditure or the energy cost of physical activity. The results of this study should be viewed in light of work by Fiatarone and colleagues (10), in which frail elderly people underwent resistance training. Interestingly, these investigators found increased spontaneous physical activity as measured from physical activity monitors.

The work of Van Etten et al. (42, 43) should be viewed in light of previous work that examined the effects of endurance exercise on total daily energy expenditure in older men and women (15). In that study, no change was found in total daily energy expenditure and free-living physical activity despite participation in a vigorous endurance exercise program. Older individuals actually reduced their energy expenditure of physical activity outside of the training program. The compensatory reduction in physical activity negated (or reduced) the direct caloric benefits associated with the endurance exercise program. The findings of these studies (15, 42, 43) are disappointing from a public health perspective. The inability of endurance or resistance training to increase free-living physical activity, despite increases in $\dot{V}O_2$ max and muscular strength, may partially explain the dismal track record of exercise (without caloric restriction) to substantially impact body weight loss. Moreover, these findings further emphasize the importance of measuring free-living total daily energy expenditure when examining the effects of exercise on body weight regulation and energy expenditure.

Resistance Exercise and Postexercise Energy Expenditure

In this brief review, we have not focused on the direct energy cost of resistance training. There are two reasons for this approach. First, the direct energetic contribution of resistance training to daily energy expenditure is likely to be very small in workouts performed by untrained individuals (≈100 to 200 kcal per workout) (43). Second, it is difficult to precisely quantify the direct energy cost of resistance training with indirect calorimetry given the nature of the exercise. Resistance training also disturbs the body's bicarbonate pools, so that the respiratory exchange ratio does not always accurately reflect whole-body fuel utilization. Furthermore, during exercise that requires significant anaerobic metabolism, oxygen consumption underestimates energy expenditure.

High-intensity exercise of long duration, however, may prolong the recovery period, contributing to significant postexercise caloric expenditure (2, 20). Such exercise may even have a residual effect on RMR when measured on the days following the highly strenuous exercise bout (7). It is possible that increases in RMR attributed to chronic exercise may result at least partially from prolonged metabolic perturbations from the previous exercise bouts.

Few studies have specifically addressed the impact of non-steady-state resistance exercise on the postexercise metabolic rate. Wilmore et al. (45) and Stone et al. (34) examined oxygen consumption during recovery from bouts of circuit training and Olympic-type weight lifting, and multiple sets of back parallel squats, respectively, but none of the calorimetry measurements extended beyond 20 min postexercise. Burleson et al. (8) reported a significantly higher excess postexercise oxygen consumption in young men 30 min, but not 60 or 90 min, following completion of a circuit of resistance exercises, in comparison to excess postoxygen consumption following steady-state aerobic exercise. In a previous study (18), we found that following a 45-min bout of resistance exercise, metabolic rate remained elevated for at least 1 hr and possibly longer compared to metabolic rate measured for 1 hr after a control condition of quiet sitting on a separate day. None of these studies examined the possibility of a prolonged effect of such exercise on metabolic rate. We previously reported that college wrestlers exhibited higher RMR values than nonwrestling controls (16, 30), suggesting that vigorous non-steady-state exercise (2.5 hr of wrestling practice) could have a residual effect on RMR when measured 12–15 hr later.

We followed-up these studies with two experiments (17) performed to determine the effects of acute strenuous resistance exercise on metabolic rate during the 2 hr immediately following exercise, and on RMR the following day (measured approximately 15 hr after cessation of exercise). In Experiment 1, beginning at 2 p.m., 7 young male subjects (previously trained in resistance exercise) completed a 90-min weight lifting protocol; their RMRs had been measured the same day at 7 a.m. Postexercise metabolic rate was measured continuously for 2 hr following exercise and compared to a preexercise baseline. RMR was measured the following morning, 15 hr after completion of the workout. In the second experiment, 6 different young men completed a similar experimental protocol as well as a control condition on a separate day in which metabolic rate was measured for 2 hr following a period of quiet sitting. For both experiments, metabolic rate remained elevated following resistance exercise for the entire 2-hr measured recovery period. The average $\dot{V}O_2$ measured 120 min after exercise cessation was elevated by 11–12%.

Resting metabolic rate measured the morning following resistance exercise compared to the previous day was 9.4% higher in Experiment 1 and 4.7% higher in Experiment 2.

We performed a third experiment (14) in which we examined postexercise energy metabolism in male subjects in response to three different treatments: a strenuous bout of resistive exercise, a bout of stationary cycling at 50% peak $\dot{V}O_2$ (with duration adjusted to approximate the estimated caloric cost of the resistive exercise), and a control condition of quiet sitting. Resting metabolic rate was measured the morning of and the morning following each of the exercise and control conditions. Oxygen consumption was measured for 5 hr following each treatment, including 2 hr immediately following each condition, at which time a standardized meal was provided and calorimetry continued for another 3 hr. Average postexercise metabolic rate was elevated for the resistance exercise treatment (mean $\dot{V}O_2 = 375$ ml $O_2 \cdot min^{-1}$) for the 5-hr recovery period relative to both aerobic exercise (mean $\dot{V}O_2 = 348$ ml $O_2 \cdot min^{-1}$) and the control condition (mean $\dot{V}O_2 = 338$ ml $O_2 \cdot min^{-1}$).

Resting metabolic rate measured approximately 15 hr postexercise for the resistance exercise condition was significantly elevated compared to the control condition. These results suggest that strenuous resistive exercise results in a greater postexercise energy expenditure compared to steady-state endurance exercise of similar estimated energy cost. Together, these three experiments suggest that strenuous resistance exercise that can be performed only by well-trained athletes (i.e., 50–60 sets of 8–12 repetitions per set performed in 90–100 min) may elevate postexercise metabolic rate for a prolonged period, with the recovery energy expenditure adding significantly to the total thermic effect of physical activity. However, resistance exercise sessions for nonathletes typically involve less total work, with fewer sets and greater rest intervals between exercise sets. Such exercise will likely induce much smaller increases in recovery energy expenditure, with less impact on total physical activity energy expenditure.

Resistance Exercise and Fat Oxidation

Maintenance of body weight and body composition requires that individuals attain both energy balance (energy intake = energy expenditure) and macronutrient balance (11, 12). Macronutrient balance is achieved when there is an equilibrium between intake and oxidation for protein, carbohydrate, and lipid. It is generally accepted that protein and carbohydrate balances are tightly regulated by mechanisms that couple oxidation to intake (11). On the other hand, changes in fat intake do not result in acute compensatory adjustments in oxidation. Thus, an increase in fat intake or a decrease in fat oxidation may promote the maintenance of body fat stores.

Fat has three properties that justify its examination in the regulation of body fat stores. First, fat stores are the ultimate buffer in deviations in energy balance (38); second, fat oxidation is not sensitive to short-term changes in fat intake (11, 38); and third, in comparison to high carbohydrate intake, diets rich in fat cause greater total energy consumption favoring both positive energy and fat balance (35). These observations suggest that among the components of macronutrient balance, fat balance is the only one that is not tightly regulated. Fat balance can thus be viewed as the vulnerable component of the system, which deserves particular attention when the metabolic characteristics of individuals predisposed to obesity are considered.

Flatt (11, 12) and Schutz et al. (32, 33) suggested that obesity is fundamentally a problem caused by a lower rate of fat oxidation relative to fat ingestion, leading to expansion of the adipose tissue mass. A low rate of fat oxidation may contribute to weight gain (28). That is, low levels of fat oxidation favor a positive fat balance, especially when accompanied by the highly palatable diet available in the U.S. According to this theory, the positive fat balance results in fat accretion during the dynamic phase of weight gain. However, as obesity becomes established, the increased adiposity, which may or may not be coupled with adipocyte insulin resistance, appears to increase plasma free fatty acids, which enhances cellular lipid oxidation. When the fat mass has increased sufficiently, fat balance is reestablished and the fat mass stabilizes. These changes allow the body to reach a new equilibrium, a point at which the rate of fat oxidation and intake are equal, albeit at a cost of obesity.

Flatt (12) suggested that, because exercise can increase total daily energy expenditure and fat oxidation, chronic exercise substitutes for expansion of the adipose tissue mass, allowing the physically active individual to achieve fat balance at a lower body fat mass. It is well recognized that for exercise of high compared to low intensity, a greater portion of the oxygen consumed is used for carbohydrate oxidation and less for fat oxidation during the exercise bout. Exercise that involves anaerobic metabolism, such as weight lifting, relies heavily on carbohydrate utilization rather than fat oxidation. During weight lifting, phosphocreatine and skeletal muscle glycogen are the major sources of fuel for the ATP synthesis required for forceful muscle contraction. Owing to these phenomena, some fitness practitioners suggest that low-intensity exercise is better than high-intensity exercise for weight and body composition regulation. Also, some may believe that for weight regulation, resistance exercise has a minimal role because carbohydrate rather than fat is the primary fuel used during weight lifting. However, as discussed below, these views fail to recognize the potential impact of high-intensity aerobic exercise and resistance exercise on 24-hr substrate utilization and fat balance. For the latter, there remains the possibility that during rest periods between sets of exercise, some fat oxidation may occur, and during the postexercise recovery period, fat is a major contributor to energy needs.

The respiratory exchange ratio (RER) is low during the first hour following strenuous weight lifting exercise (14, 17, 18), often falling below .70. The RER, however, does not reflect true substrate oxidation rates. It appears that the major contributor to the low postexercise RER immediately following exercise (i.e., during the first hour of recovery) is the replenishment of the bicarbonate ion pool (metabolically produced CO_2 is being conserved, which lowers the $\dot{V}CO_2$ and the RER), and thus it is unclear how much fat is actually oxidized. However, in two of our studies (14, 17), we found the RER to be lower 15 hr following a strenuous bout of weight lifting, a time at which the RER would no longer be affected by changes in the bicarbonate ion and would thus reflect greater fat oxidation. It appears, then, that fat oxidation is enhanced during recovery from resistance exercise as well as other high-intensity exercise, thus sparing available carbohydrate for glycogen resynthesis.

Little is known about the effect of resistance exercise training on daily fat oxidation. Van Etten et al. (42) examined the effect of a 12-week weight training program on substrate utilization during sleep in 21 male subjects. They found a significant pre- to posttraining increase in fat oxidation during a portion of the sleep period, but for the entire designated sleep period from midnight to 6 a.m., there was no statistically significant pre- to posttreatment increase in fat oxidation. Interestingly, there was a remarkably strong inverse correlation between the pretraining rate of fat oxidation during sleep and the pre- to posttraining change in fat oxidation during sleep. Van Etten et al. concluded that weight training in young men increases relative fat utilization in individuals who oxidize fat at a low rate but decreases fat utilization in those who exhibit a high pretraining fat oxidation.The reason for this differential response in fat oxidation to resistance exercise training is unclear. While novel and interesting, these findings await confirmation from other laboratories.

Ballor and colleagues (3) studied the effect of aerobic and resistance exercise on fat oxidation in individuals who had previously lost weight by dieting. The authors hypothesized that exercise training would help the individuals maintain their weight by increasing fat oxidation both at rest and during the postprandial period. However, neither mode of exercise reversed the weight loss–induced decrease in resting and postprandial fat oxidation. Ballor et al. concluded that when weight loss is maintained through exercise training, the mechanism for this maintenance is not exercise-induced enhancement of resting and postprandial fat oxidation.

Treuth et al. (40), studying healthy older women, examined the effect of a 16-week strength training program on 24-hr substrate utilization as measured in an indirect room calorimeter. At the end of the training program, they found daily fat oxidation to be almost double compared to pretraining values. Findings from this study also await confirmation.

These disparate findings from many studies indicate that there is much to learn regarding the effects of both acute and chronic resistance exercise on energy expenditure and balance and on fat oxidation and balance. The effects of resistance exercise on energy balance and weight regulation should be evaluated on the basis of its overall impact on total energy expenditure, spontaneous physical activity energy expenditure, 24-hr substrate utilization, and energy and macronutrient intake over time, rather than solely on its impact on energy expenditure and fuel utilization during the exercise bout itself. Additional research is needed to address the impact of both acute and chronic weight lifting exercise on 24-hr energy and macronutrient balance.

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