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Alterations in energy balance with exercise^{1,2}

Klaas R Westerterp

ABSTRACT The doubly labeled water method for measuring average daily metabolic rate (ADMR) in combination with resting metabolic rate (RMR) allows one to assess the relation between exercise and energy balance. Three topics were included in an analysis of available data: 1) the limits of energy turnover in relation to physical performance for the achievement of energy balance, 2) the effect of an exercise intervention on daily energy turnover and its components, and 3) the effect of exercise on body composition. In the general population, physical activity level (PAL: ADMR/RMR) ranges between 1.2 and 2.2–2.5. There is no sex difference in the level of physical activity. Higher PAL values can be maintained by training and supplementation of the diet with energy-dense, carbohydrate-rich formulas. Exercise training does not influence spontaneous activity except in the elderly. In sedentary subjects, exercise training does not influence RMR when body weight is maintained. An exercise-induced increase in ADMR is about twice the training load. Exercise induces an increase in fat-free mass, especially in women, and a decrease in fat mass. Women tend to preserve energy balance and consequently loss of fat mass is significantly less. *Am J Clin Nutr* 1998;68(suppl):970S–4S.

KEY WORDS Energy intake, average daily metabolic rate, resting metabolic rate, basal metabolic rate, physical activity level, diet-induced energy expenditure, activity-induced energy expenditure, exercise training, fat-free mass, fat mass

INTRODUCTION

Adult humans generally maintain a balance between energy intake and energy expenditure. The energy store of the body does not fluctuate much, as the constancy of body weight and body composition shows. The main component of the daily energy turnover (average daily metabolic rate, ADMR) in the average subject is the energy expenditure for maintenance processes, usually called resting metabolic rate (RMR). The remaining components of ADMR are the diet-induced energy expenditure (DEE) and the activity-induced energy expenditure (AEE). DEE is a fraction of $\approx 10\%$ of energy intake, depending on the macronutrient composition of the food consumed. AEE is the most variable component of the daily energy turnover, ranging between an average of 25–35% of ADMR up to 75% in extreme situations during heavy, sustained exercise. Today it is hard to find people working at this level in daily life, but endurance sports take people up to their limits. Here, we will focus on energy turnover in relation to energy balance and body composition.

The doubly labeled water method allows accurate measurement of ADMR in unrestricted conditions for periods of 1–3 wk to assess the relation between exercise and energy balance. Recently, Black et al (1) reviewed 574 measurements of ADMR, taken with use of the doubly labeled water method, including 66 in soldiers in training exercises and 49 in athletes and explorers. This data, plus results of studies on exercising subjects published afterward, is the basis for the present analysis, which will focus on 3 topics: 1) limits of energy turnover in relation to physical performance for the achievement of energy balance; 2) the effect of an exercise intervention on daily energy turnover and its components; and 3), the effect of exercise on body composition.

LIMITS OF ENERGY TURNOVER IN RELATION TO PHYSICAL PERFORMANCE FOR THE ACHIEVEMENT OF ENERGY BALANCE

Black et al (1) theorized that there are boundaries for activity levels within the general population. They suggested a range for the physical activity level (PAL: ADMR/RMR) of 1.2–2.5 for sustainable lifestyles. At PAL values of ≈ 2.5 , subjects have problems maintaining energy balance. Five studies in soldiers during field training (2–6), with a combined total of 66 subjects with a PAL value of ($\bar{x} \pm SD$) 2.40 ± 0.46 (1), all reported a negative energy balance over the observation interval. The body weight loss ranged from 0.4 to 2.3 kg/wk.

Examples in which energy balance is maintained at PAL values > 2.5 have been shown in studies in endurance athletes such as runners (7, 8), cross-country skiers (9), and professional cyclists (10). The explanation of the difference between these studies and those in soldiers is probably 2-fold. First, professional endurance athletes are a selection of the population trained over many years to reach a high level of performance. Second, endurance athletes manage to maintain energy balance at a high level of energy turnover by supplementing the diet with energy-dense, carbohydrate-rich liquid formulas (11).

The adaptation of food intake to the high energy requirements of high-intensity endurance exercise is an important aspect of the maintenance of energy balance. Edholm et al (12) showed that intake tended to be low on days when the expenditure was very

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high, and the difference was made good some days later when expenditure was lower. Apparently, high-intensity endurance exercise reduced appetite, and subjects needed time to adjust their energy intake to the increased energy requirements. The average discrepancy between energy intake and energy expenditure in the studies in soldiers during field training (2–6) ranged from 2 to 8 MJ/d or 20 to 90 MJ over the observation interval of 7–25 d. Some studies presented information on changes in energy intake over the observation interval, again showing that there was a tendency for a decrease in the discrepancy between intake and expenditure in the subjects over time, either by decreased expenditure (4) or increased intake (3).

None of the studies in soldiers during field training mention the use of energy-dense, carbohydrate-rich liquid formulas during exercise. These energetic drinks constitute a substantial portion of energy intake in professional athletes. Sjödin et al (9) reported a contribution of 16% of energy intake and 25% of carbohydrate consumption by carbohydrate-rich formulas in athletes with an average energy turnover of ≤ 34.9 MJ/d over a 6-d training interval. Athletes studied in the Tour de France reached an average energy turnover of ≤ 38.0 MJ/d (10). In these 2 studies (9, 10), subjects maintained energy balance at the reported levels of energy turnover. In the athletes studied in the Tour de France, body mass and body composition did not show significant changes over the 23-d race. In the study of Sjödin et al (9) in a 6–7-d training camp of the Swedish national team of cross-country skiers, it was shown that energy intake matched energy turnover in the short term. The mean difference between energy turnover and energy intake for the group of 4 women and 4 men was 0.1 ± 1.9 MJ/d.

There is a clear sex effect on ADMR in the general population, with ADMR in females being 11% lower than in males of the same age and body size (1). Indeed, in an analysis of existing data sets with observations in healthy subjects aged 18–49 y, ADMR in women was lower than in men, 10.0 ± 2.2 MJ/d compared with 13.6 ± 2.6 MJ/d ($P < 0.001$), respectively (13). The reason for the difference in ADMR between women and men is probably the difference in body composition. Plotting ADMR as a function of fat-free mass (FFM) for subjects of the latter study resulted in the same linear relation for women and men (Figure 1). Adding to this the data points of professional athletes clearly shows that men reach higher ADMR levels because of their higher FFM (Figure 1) and thus can reach higher levels of physical performance.

In conclusion, in the general population PAL ranges between 1.2 and 2.2–2.5. There is no sex difference in the level of physical activity when adjusted for FFM. Higher PAL values can be maintained by training; energy balance can be maintained by supplementation of the diet with energy-dense, carbohydrate-rich formulas.

EFFECT OF EXERCISE INTERVENTION ON DAILY ENERGY TURNOVER AND ITS COMPONENTS

A few well-controlled studies have measured the effect of exercise intervention on ADMR (Table 1). Additionally, 2 studies have been conducted on the effect of exercise intervention on ADMR in combination with energy restriction in obese subjects (19, 20). The largest effect of exercise on ADMR was measured in 2 studies with jogging as means of increasing physical activity (Table 1). The other 3 included indoor exercises, stationary

cycling on a cycle ergometer, and weight-training in a limited number of sessions per week. Bingham et al (14) accentuated the difference between the nontraining and training intervals by limiting the activity level in the nontraining interval to light activities. Subjects were allowed ≤ 15 min walking outside per day, and no other exercise, ie, cycling and sports, was permitted. The other studies limited the energy expenditure associated with physical activity in the nontraining interval by recruiting subjects who were not engaged in regular exercise. There are 3 points that will be discussed in more detail: the effect of an exercise intervention on spontaneous physical activity, the size of the change in energy expenditure associated with physical activity in relation to the training load, and the effect of an exercise intervention on RMR.

All 5 exercise intervention studies shown in Table 1 reported on the effect of the exercise intervention on spontaneous physical activity. Subjects in the study of Bingham et al (14) kept activity diaries to the nearest minute over the last week of the control period and in weeks 2, 3, or 4, and week 9 of the training period. Time spent running, walking, and participating in sports increased from ($\bar{x} \pm \text{SE}$) 15 ± 2 min/d (restricted maximum) in the control period to 131 ± 16 min/d in the last training week; 37 min/d of the latter was running during training. Blaak et al (15) conducted an activity interview that showed no difference in the weekly number of minutes of each activity category outside the training hours before and during the last 2 wk of training. Goran and Poehlman (16) calculated the energy expenditure associated with nontraining activity from the difference between ADMR and RMR after adjusting for thermic response to feeding and energy cost of the training exercise, showing a reduction from ($\bar{x} \pm \text{SD}$) 2.39 ± 1.62 MJ/d before to 1.42 ± 1.89 MJ/d during the last 10 d of training. Westerterp et al (17) and Van Etten et al (18) monitored activity with a triaxial accelerometer before, at 8 wk, and at 18–20 wk of training. Average weekly accelerometer output, excluding the training time, did not change. In conclusion, the exercise interventions did not affect spontaneous physical activity in all but one study, which was in elderly subjects (16). The authors suggested that the level of

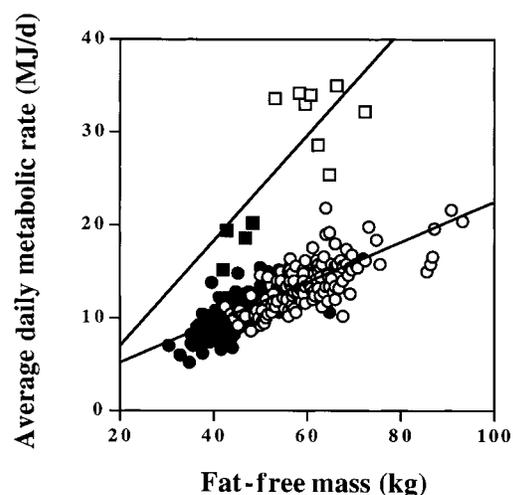


FIGURE 1. Average daily metabolic rate plotted as a function of fat-free mass in healthy adults (●, women; ○, men) and in professional athletes (■, women; □, men), with the calculated linear regression lines for both groups.

TABLE 1
Studies measuring the effect of exercise intervention on average daily metabolic rate (ADMR)

Reference	Intervention		Subjects	Age	Δ ADMR ¹
	Duration	Activity			
	wk		<i>n</i>	<i>y</i>	%
Bingham et al, 1989 (14)	9	Jogging ≤ 1 h/d	2W, 3M	24–33	27 \pm 17
Blaak et al, 1992 (15)	4	Five 1-h cycling sessions	10M	10–11	12 \pm 6
Goran and Poehlman, 1992 (16)	8	Three cycling sessions	5W, 6M	56–78	3
Westertep et al, 1992 (17)	40	Jogging up to 50 km/wk	5W, 8M	28–41	21 \pm 9
Van Etten et al, 1997 (18)	18	Two weight-training sessions	12M	23–41	9 \pm 8

¹ $\bar{x} \pm$ SD.

exercise during the last week of training (3 h/wk at 85% $\dot{V}O_{2\max}$) was too vigorous and thus fatigued the elderly participants for the remainder of the day.

The effect of the exercise intervention on RMR or basal metabolic rate (BMR) was measured in each of the studies. Bingham et al (14) did not observe any change in BMR, overnight metabolic rate, or sleeping metabolic rate (SMR). Blaak et al (15) observed no change in SMR. Goran and Poehlman (16) observed an increase in RMR from 6.68 to 7.38 MJ/d. Westertep et al (17, 21) observed a tendency for SMR to decrease from ($\bar{x} \pm$ SD) 6.46 \pm 0.62 to 6.32 \pm 0.61 MJ/d. Van Etten et al (18) did not observe any change in SMR. All studies measured RMR or BMR ≥ 36 h after the last training to prevent any carryover effect from the prior exercise bout. The overall conclusion of the exercise intervention studies is that there is no clear long-term effect of exercise on RMR. The lack of a systematic change in RMR is surprising because most studies showed an exercise-induced increase in FFM, an important determinant of RMR. The longest training intervention showed the biggest absolute change in FFM without any indication of an increase in RMR. In fact, the opposite was measured, SMR was slightly lower, whereas FFM had increased by 5%, at 40 wk after the start of the training program (21). Here, the speculation was that RMR changed as a defense mechanism of the body weight maintenance. Body mass decreased by 1.0 \pm 1.7 kg during the training program whereas FFM increased 2.7 \pm 1.5 kg and fat mass decreased 3.7 \pm 2.1 kg. The decrease in body mass explained 38% of the variance in the decrease in SMR. The results are in contrast with findings in elite athletes, who maintain body mass at extremely high ADMR levels (*see above*). Sjödin et al (22) reported a 13–16% higher BMR in a group of elite cross-country skiers 39-h after their last training session.

The size of the change in energy expenditure associated with physical activity is generally higher than the energy cost of the training intervention. Van Etten et al (18) summarized the results of this aspect of the 5 studies mentioned above. The net energy cost of the training interventions were (in MJ/d) 1.9 (14), 0.6 (15), 0.6 (16), 0.9 (17), and 0.5 (18), whereas the change in energy expenditure associated with physical activity was 2.8, 1.3, -0.3, 2.2, and 1.2 MJ/d, respectively. With the exception of the intervention in elderly subjects, the size of the change in energy expenditure associated with physical activity was on average twice the energy cost of the training intervention. Combining these results with the conclusion mentioned above, that the exercise interventions did not affect spontaneous physical activity in all but the study in elderly subjects, implies that the energy cost of the training intervention was twice as high as expected from measurements or calculations of energy expendi-

ture during the imposed exercise. We can only speculate on reasons for the 2-fold increase in ADMR compared with the expectation. The most likely explanation is excess postexercise energy expenditure. As mentioned above, all studies measured RMR or BMR ≥ 36 h after the last training session to prevent any carryover effect from the prior exercise bout. Whatever the reason might be, the discrepancy between the expected increase and the measured increase in ADMR is a function of the training time. This is most clearly illustrated in the study of Westertep et al (17) in which 7 subjects were measured at the start and 8, 20, and 40 wk after the start of training. The training volume doubled from 25 to 50 km/wk without any change in ADMR (**Figure 2**). Apparently, the effect of an exercise intervention on daily energy turnover decreases in time, ie, novice runners increase the efficiency of the exercise as a result of the training.

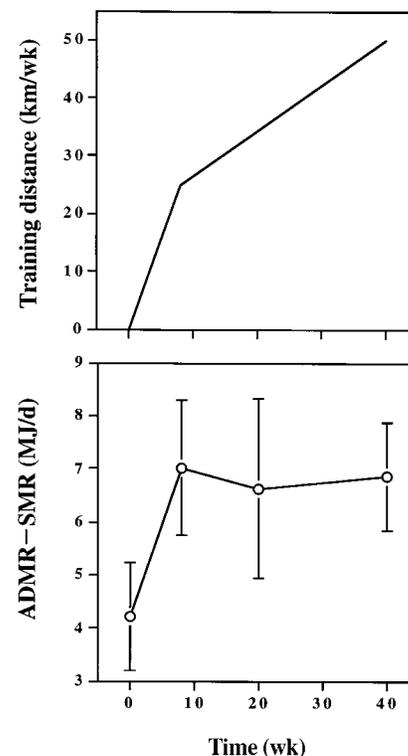


FIGURE 2. Training distance and nonresting energy expenditure [average daily metabolic rate (ADMR) minus sleeping metabolic rate (SMR)] in 7 novice athletes (3 women and 4 men) at baseline and 8, 20, and 40 wk after the start of a training period in preparation for the half-marathon (adapted from reference 17).

In conclusion, exercise training does not influence spontaneous activity except in the elderly. In sedentary subjects, exercise training does not influence RMR when body weight is maintained. Finally, an exercise-induced increase in ADMR is about twice the training load.

EFFECT OF EXERCISE ON BODY COMPOSITION

There have been ≥ 3 meta-analyses of the relation between physical activity as derived from ADMR measured with use of the doubly labeled water method and body composition (13, 23, 24). Additionally, there have been the 5 exercise intervention studies (Table 1) measuring the effect of a change in physical activity on body composition.

Westerterp et al (23) analyzed 96 existing data sets with observations on height, fat mass, FFM, and PAL. FFM and fat mass were related to PAL. In a regression analysis, fat mass explained 53% and 40% of the variation in FFM in females and males, respectively. Adding PAL to the model raised the explained variation in FFM in females to 62%. In contrast with females ($r = 0.10$, NS), there was an independent relation between PAL and fat mass in males ($r = -0.41$, $P < 0.05$), such that a higher PAL was related to a lower fat mass. It was concluded that there is a relation between PAL and FFM under normal living conditions, although fat mass obscures the relation, especially in males. When subjects lose fat mass they also lose FFM, an effect that partly explains why exercise does not prevent the loss of FFM when the loss of fat mass is high as in persons on weight-reducing diets. Schulz and Schoeller (24) analyzed 259 existing data sets with observations on body fatness and PAL as assessed with use of the doubly labeled water technique. The relation between PAL, here expressed as nonbasal energy expenditure divided by body weight (ADMR - RMR)/kg, and body fatness [FM divided by body weight (FM/kg)] was highly significant. Fatness increased with decreasing PAL and it was suggested that a low PAL is a permissive factor for obesity.

Westerterp and Goran (13) analyzed existing data sets with observations on ADMR, RMR, and percentage body fat that included 290 healthy subjects aged 18–49 y. PAL was quantified by adjustment of ADMR for RMR as suggested by Carpenter et al (25). The result was a sex difference in the relation between PAL and body composition. In males, there was a significant inverse cross-sectional relation between activity energy expenditure and percentage body fat, whereas no such relation was apparent in females. The suggested implication was that females probably do not lose much fat when they adopt a higher PAL.

The 5 exercise intervention studies summarized in Table 1 reported no significant changes in body weight (14–16, 18) or small changes (< -1 kg over 40 wk) (17). Apparently, an exercise-induced increase in ADMR is compensated for by an increase in energy intake, as might be expected. However, all 5 studies showed a significant increase in FFM and some showed a decrease in fat mass (16–18). The most pronounced changes in body composition were observed in the longest exercise intervention study, a 40-wk training of novice athletes in preparation for a half-marathon, a running contest of ≈ 21 km (17). In men, the change in fat mass was significantly correlated with the initial fat mass of the subject ($P < 0.001$). That is, subjects with a higher initial fat mass lost more fat than those who were leaner at the start. This was not so in women, despite higher initial fat mass (Figure 3). Women tend to preserve their energy balance more

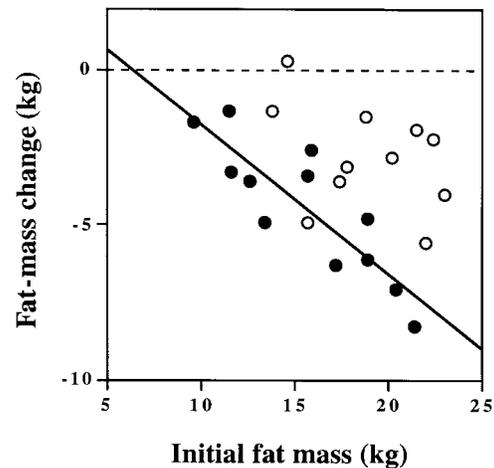


FIGURE 3. Fat-mass change from baseline until 40 wk after the start of a training period in preparation for a half-marathon in male (●) and female (○) subjects with the calculated regression line for men ($P < 0.001$; adapted from reference 17).

strongly than men, and consequently, the loss of fat mass is significantly less. The sex difference is probably attributable to an increased energy intake in women. The men's reported energy intake after 8, 20, and 40 wk of training was significantly lower than their ADMR. In the women, differences between intake and expenditure were not significant at any stage of the training program. It must be that women compensate for an activity-induced increase in energy expenditure with more of an increase in energy intake than men do, though the evidence—less loss of fat mass—is indirect. Direct evidence from food intake measurements is not available because the measurement of habitual food consumption in humans is one of the hardest tasks in energy balance studies.

In conclusion, exercise induces an increase in FFM, especially in women, and a decrease in fat mass. Women tend to preserve their energy balance and consequently their loss of fat mass is significantly less. 

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