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Article *in* Medicine & Science in Sports & Exercise · December 1993

DOI: 10.1249/00005768-199312000-00014 · Source: PubMed

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ABSTRACT

EDWARDS, J. E., A. K. LINDEMAN, A. E. MIKESKY, J. M. STAGER. Energy balance in highly trained female endurance runners. *Med. Sci. Sports Exerc.* Vol. 25, No. 12, pp. 1398–1404, 1993. Anecdotal and scientific reports have suggested that some female endurance athletes may have an inexplicable imbalance between energy intake and energy expenditure. We compared energy intake (EI) from food diaries (FD) with assessment of free-living energy expenditure (EE) using doubly labeled water (DLW) and a food attitude survey for 7 d in nine female distance runners. Daily EE via DLW (2990 ± 415 kcal) was greater ($P < 0.01$) than daily EI via FD (2037 ± 298 kcal): a 32% imbalance. Body weight did not change during the 7 d (day 1, 55.3 ± 6.2 kg; day 7, 55.1 ± 5.6 kg). A positive relationship was observed between EE and body weight (r = 0.82) while a negative correlation existed between EE vs EI (r = −0.83) and between EI vs body weight (r = −0.74). A negative correlation was observed between body weight and food attitude/body image (r = −78), i.e., the heavier women self-reported lower EI and also reported lower body image scores. These female athletes had a significant imbalance between EI and EE by our measures. Since body image and EI were related to body weight, the estimates of EI may be low due to underreporting particularly by the heavier athletes.

DOUBLY LABELED WATER, ENERGY EXPENDITURE, WOMEN ATHLETES, FOOD INTAKE, ENERGY EFFICIENCY, STABLE ISOTOPES

Anecdotal and scientific reports have suggested that some female endurance athletes may have surprisingly low energy intakes whereas the purported physical performances suggest a high level of energy expenditure (3,22,33). Studies, primarily designed to investigate the etiology of athletically induced amenorrhea or its long-term consequences, such as lowered bone mineral content, have given early indications of relatively low energy intakes (7,13,19,21,23). Reported intake values for women endurance runners in these studies range from 5860 $kJ \cdot d^{-1}$ to 8330 $kJ \cdot d^{-1}$, values that appear to be impossibly low given the extent and rigor of the training programs in which these women participate.

0195-9131/93/2512-1398$3.00/0
MEDICINE AND SCIENCE IN SPORTS AND EXERCISE

Submitted for publication October 1993.
Accepted for publication August 1993.

Without exception, stable body weight is dependent upon the balance between energy intake and energy expenditure. While day-to-day differences may exist between the two, to be in accordance with the laws of thermodynamics, long-term energy balance must be maintained for weight to remain constant. Therefore, to ensure accurate assessment of energy balance, it is necessary that the instruments used to measure energy intake and energy expenditure be valid and reliable and of sufficient duration.

Energy and nutrient intake can be estimated by a number of different methodologies, including dietary histories, food frequency lists, food records (usually 3–7 d), 24-h dietary recalls, and weighed food intake (controlled diets). Food records are most commonly used in assessing intake of athletes due to ease of administration, reliability, and low cost (2). However, several sources of measurement error can decrease the accuracy of self-recorded food intake (11).

Energy expenditure has usually been estimated by some combination of activity diaries and factorial methods in which activities are summed for total time and multiplied by an energy equivalent (10). In 1982, the doubly labeled water method of measuring free-living energy expenditure was first used in human research (26). Since then, the results from various validation studies have lead to the conclusion that the method is as accurate as respirometry and has a precision of 2–8%, depending on the amount of isotope ingested and rate of isotope turnover (28). The increased accuracy and precision of the doubly labeled water method should, therefore, allow a more precise assessment of energy expenditure.

The question remains, therefore, as to the source of this purported discrepancy in energy balance reported in the highly trained women runners. Has food intake been underestimated or energy expenditure overestimated, or some combination of these two? Perhaps the previous estimates of energy intake and energy expenditure are correct and these women possess some previously unidentified mechanism for extreme energy efficiency. First principles would require that we establish that the reports of energy imbalance with weight maintenance be confirmed using the most accurate methods possible.

Therefore, the purpose of this study was to compare energy intake as measured by self-reported food diaries with energy expenditure as measured by doubly labeled water in a group of free-living, highly trained female endurance runners. In addition to detailed dietary analysis, a food attitude survey was administered as a screening tool for eating disorders and to assess the athletes' attitude toward food in general, and toward their body image, specifically.

METHODS

Subjects

Nine, highly trained, apparently healthy women from the university's cross-country team were recruited as subjects for this study. Athletes received written and verbal explanations of the experimental procedures and informed consent was obtained from them in accordance with the University's Human Subject Protection Policy. Subject characteristics are reported in Table 1 (age, height, weight, BMI, body fat, lean body mass). Seven of the women were eumenorrheic and two were oligomenorrheic as determined by a menstrual status questionnaire (17). As for training, the women as a group, averaged 6.5 ± 0.9 miles$\cdot d^{-1}$ running as well as two, 45 min, resistance-training sessions during the metabolic measurement period.

Initial Training and Screening

The nine subjects reported their nutritional, menstrual, and training histories and completed a Food Attitude Scale (FAS) (32). The FAS, with instrument reliability established at 0.71, is a 30-item questionnaire using a Likert-type scale to assess attitudes related to food and eating in four domains: emotional, aesthetic-sensory, social-celebrative, and body image. Overall FAS scores usually range from 30–150, with higher scores denoting a more positive and healthy attitude toward food. A registered dietitian received 24-h food and activity recalls on each subject using food models and pictures as visual aids. Subjects were then instructed to maintain food and activity records for two more days and then return the forms. After analysis, the food and activity records were returned to the subjects with comments on how to increase accuracy of recording. No evaluations or suggestions for change in food intake were made.

TABLE 1. Subject characteristics.

Subject	Height (cm)	Weight (kg)	BMI ($kg \cdot m^{-2}$)	LBM (kg)	% Body Fat
1	170.2	48.00	16.57	41.50	13.5
2	166.4	49.40	17.84	40.30	18.3
3	160.0	50.20	19.61	45.00	10.4
4	167.6	50.20	17.87	46.40	7.7
5	170.2	54.50	18.81	48.00	12.0
6	165.1	57.90	21.24	48.40	16.3
7	169.6	61.30	21.31	53.10	13.3
8	172.7	62.20	20.85	53.60	13.9
9	180.0	63.90	19.72	56.70	11.2
Mean	169.1	55.29	19.32	48.10	13.0
SD	5.5	6.18	1.67	5.60	3.2

Energy Intake (EI)

On day 1 of the metabolic study period, the subjects were instructed by the same dietitian to maintain food and activity records, just as they had done during the previous training in the use of food diaries. On day 7, all records were returned and reviewed for accuracy. Energy intake was analyzed with the use of Nutritionist III software program.

Energy Expenditure by Doubly Labeled Water (EE)

Isotope dosage. Each subject's body weight was measured to the nearest 0.1 kg to allow for the estimation of total body water (TBW = body weight × 0.65) and subsequently calculation of the isotope dose required. The exact DLW (D_2O, 0.16 $g \cdot kg^{-1}$ estimated TBW; $H_2{}^{18}O$, 0.30 $g \cdot kg^{-1}$ estimated TBW) dosage was determined by weighing the delivery vessel before and immediately after filling to 0.1 mg. After ingestion the delivery vessel was then rinsed with 100 ml of tap water, which was immediately ingested to ensure total dosage delivery. Urine samples for measurement of isotopic enrichment were collected immediately prior to DLW administration and on the second voiding, 5 h post-ingestion. Urine samples were collected on days 2 and 4, with a final urine sample collected on day 7. An aliquot of the DLW was reserved for later dose-dilution determination of actual isotopic enrichment.

Isotopic analysis. The urine collected was divided into two aliquots for subsequent determinations of isotopic compositions. Measurements of ^{18}O were carried out in duplicate by equilibration of the water, which had been vacuum distilled from the urine, with carbon dioxide (4). The analysis of ^2H were carried out in triplicate by reduction of the water component to hydrogen gas in the presence of zinc (5). Both gases were measured, relative to laboratory working standards, on a Finnigan MAT Delta E gas isotope ratio mass spectrometer. All analyses for a given subject were done on the same day and included an analysis of the diluted dose for determination of the isotopic composition of the dose ingested.

Total body water was calculated from the weighted average of the two isotope dilution spaces (TBW = $[N_O + (N_D * 0.97)]/2$) using the generalized formula $N_x = (d/MW)(APE/100)(18.02)[f/(R_{Std} \cdot \Delta\delta \text{ isotope})]$, in which N is the isotope dilution space for either deutrium or ^{18}O, d is the dose in grams, MW is the molecular weight of the dose, APE is the atoms percent excess of the dose relative to the body water, f is the fractionation factor for each isotope, respectively (^2H = 1, ^{18}O = 1.0407 @ 25°C), R_{Std} is the ratio of heavy to light isotope in the standard (SMOW), and $\Delta\delta$ is the arithmetic difference between the physiological sample before and after enrichment. The isotope elimination rates, k_O and k_H, were calculated using the two-point method where $k = (\ln APE_{final} - \ln APE_{initial})/\Delta t$. The mean daily carbon dioxide production ($mol \cdot d^{-1}$) was calculated using the formula, $rCO_2 = (N/2.078)(1.01k_O - 1.04k_H) - 0.0246r_{Gf}$, where r_{Gf} is estimated as $1.05N(k_O - k_H)$ (27). Energy equivalent for CO_2 was calculated as: Eeq_{CO2} ($kJ \cdot l^{-1}$) = 15.48/RQ + 5.5 (9).

Statistical Analysis

Descriptive statistics including means and standard deviations were computed for all variables. Differences between mean EE and EI were analyzed by use of a dependent *t*-test. Pearson product moment correlation coefficients were computed to determine the relationships between EE, EI, body weight, and body image. Statistical significance was established at $P < 0.05$; however, actual P values are reported for each variable.

RESULTS

The demographic data for the women are presented in Table 1. Initial body weight did not differ from the body weight observed following the 7-d assessment period (55.28 ± 6.18 kg vs 55.12 ± 5.55 kg (mean ± SD)). As expected, the percent body fat calculated from the TBW measure (Fat free mass = TBW/0.73, Fat mass = Body weight − Fat free mass) was low (13.0 ± 3.4%) when compared with values reported for sedentary women of the same age, although the results may be depressed due to the inherent variability of the stable isotope methodology. TBW from isotope dilution was found to be 35.1 ± 3.9 l, which was 63.5% of total body weight.

The rank order of the women runners by body weight is illustrated in Table 2. The values for EI and EE are also shown in Table 2. When compared, a statistically significant difference between the two measures, EI = 8527 ± 1246 $kJ \cdot d^{-1}$ vs EE = 12,516 ± 1737 $kJ \cdot d^{-1}$ (P = 0.003) was observed. Food intake represented 68% of the EE as measured by DLW.

TABLE 2. Subjects rank ordered by weight.

Subject	Weight (kg)	EI (kJ)	EI/Wt ($kJ \cdot kg^{-1}$)	EE (kJ)	EE/Wt ($kJ \cdot kg^{-1}$)	EE − EI (kJ)
1	48.00	10,034	209	10,465	218	431
2	49.40	8,376	170	11,654	236	3,278
3	50.20	8,573	171	11,491	229	2,918
4	50.20	9,938	198	11,934	238	1,997
5	54.50	9,594	176	11,022	202	1,427
6	57.90	8,765	151	12,386	214	3,621
7	61.30	6,233	102	14,835	242	8,602
8	62.20	7,585	122	15,626	251	8,041
9	63.90	7,644	120	13,228	207	5,584
Mean	55.29	8,527	158	12,516	226	3,989
SD	6.18	1,246	37	1,737	17	2,855

Energy intake (EI) and energy expenditure (EE) are reported in kilojoules. Subjects 3 and 8 oligomenorrheic; all others eumenorrheic.

Figure 1 illustrates the relationship between EE and EI in this sample of women endurance runners. A significant negative correlation (r = −0.83) was found to exist between the two measures, i.e., the higher the energy expenditure the lower the reported food energy intake. Figure 2 reflects the relationship between EE by DLW and body weight. A positive correlation between EE and body weight (r = 0.82) indicates that the heavier women generally expended more energy than the lighter women. Figure 3 depicts the relationship between body weight and EI, which indicates that heavier runners reported taking in less food (r = −0.74). Figure 4 reinforces the negative relationship between body size, as measured by BMI, and the difference between EI and EE. The larger the BMI the greater the difference between energy intake reported and energy expenditure as measured by DLW (r = −0.79).

The final graph, Figure 5, illustrates the association between BI and body weight. These measures were

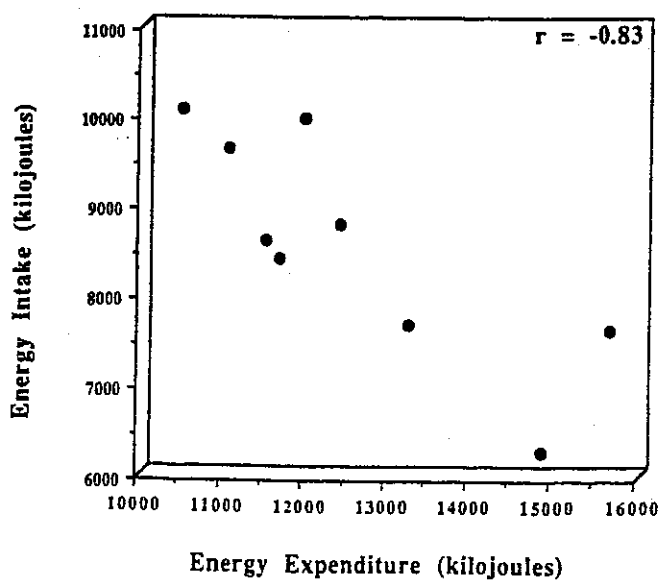

Figure 1—The relationship between energy expenditure as measured by doubly labeled water and energy intake as determined by food diary (N = 9, r = −0.83).

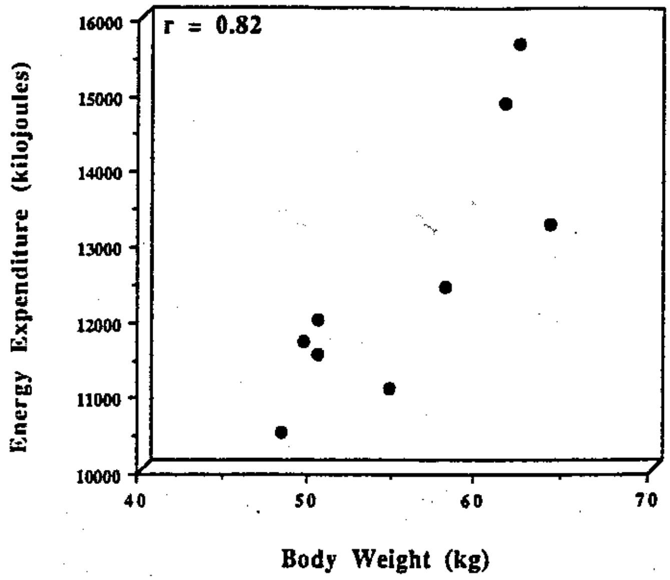

Figure 2—The relationship between the body weight of the women athletes and energy expenditure as measured by doubly labeled water ($N = 9$, $r = 0.82$).

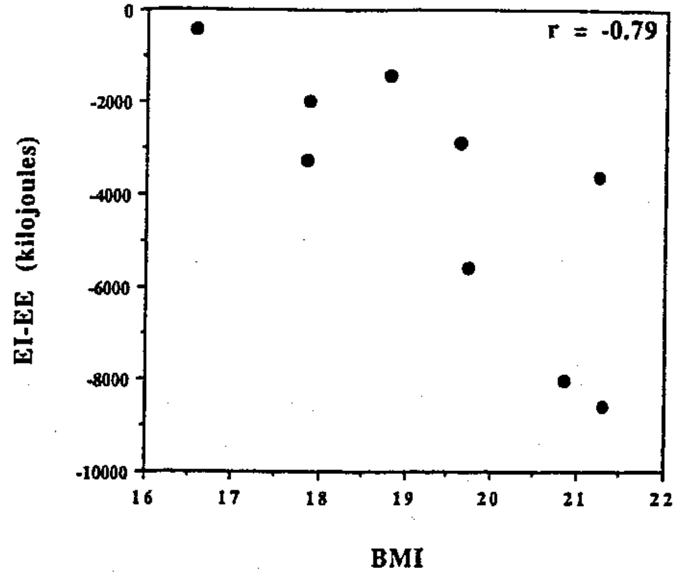

Figure 4—The relationship between body mass index (BMI) and the difference between energy intake and energy expenditure ($N = 9$, $r = -0.79$).

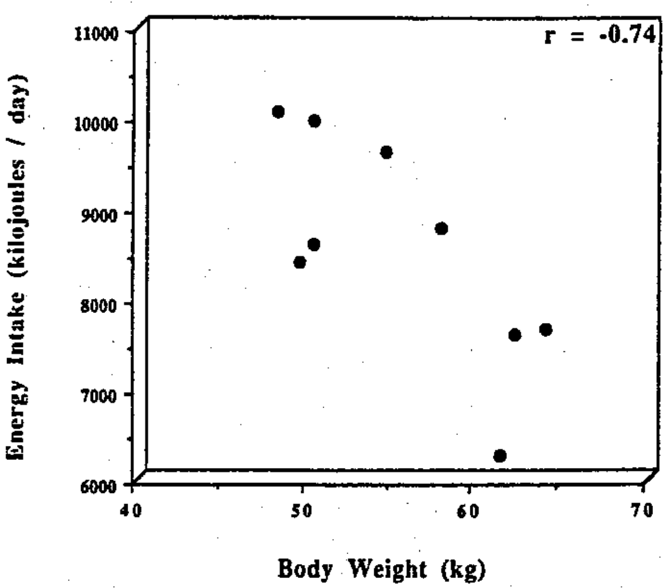

Figure 3—The relationship between the body weight of the women athletes and energy intake as determined by food diary ($N = 9$, $r = -0.74$)).

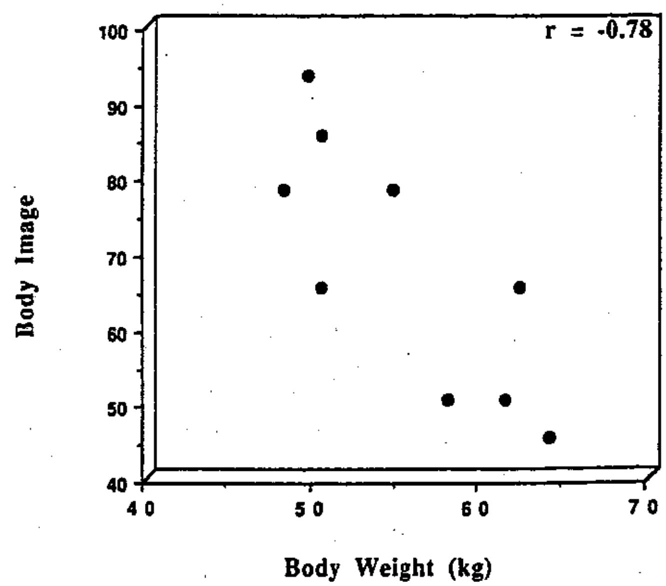

Figure 5—The relationship between the body weight of the women athletes and body image as determined by the Food Attitude Scale ($N = 9$, $r = -0.78$).

observed to be negatively correlated ($r = -0.78$), which suggests that the heavier females possessed lower body images, i.e., less satisfaction with their bodies.

DISCUSSION

Several investigations have measured food energy intake by dietary diaries and/or dietary recall. The reported food energy intakes range from 6400 $kJ \cdot d^{-1}$ to 11,000 $kJ \cdot d^{-1}$ (6,7,19,21,23,25). In all of these studies the authors express surprise at the perceived low energy intake vs the purported energy expenditure by their respective subjects. Yet, none of these studies actually measure energy expenditure. In most cases only the training mileage the subjects had run was recorded and therefore no true energy balance could be determined.

Energy Intake

The discrepancy between reported energy intake and energy expenditure may be explained in part by underreporting of food intake (18). Mertz et al. (20) found underreporting quite common among both adults and adolescent males, at rates of 81% and 84%, respectively.

By subsequently controlling the subjects' dietary intake, the researchers found that this underreporting represented 18–20% of energy required to maintain weight. In the present study, the women runners probably also under reported, possibly from 4–58% of total energy intake.

Underreporting may be subconscious. Psychological factors affecting the incidence of underreporting are not well known, nor have strategies to control these factors been successful (2,11,20,31). These factors may vary by population groups, e.g., obese, athletes, men, women, etc. (20). In the study population of elite women endurance runners, the athlete's perceived body image was inversely related to body weight. There was also a greater discrepancy in EI and EE in the heavier than in the lighter runners. A subject's perceived body image may affect accuracy in reporting foods consumed, i.e., the poorer the body image, the greater the underreporting. Mertz et al. (20) suggest that under reporting, though subconscious, may be motivated by the belief that low body weight is accomplished through eating less. In a sport such as endurance running, where the image is of a petite and lithe runner, the taller and heavier runners may be trying to deal with the image as well as the sport.

Energy Expenditure

The use of the doubly labeled water method as a measure of energy expenditure was first proposed by Lifson, Gordon, and McClintock in 1955 (15). Due to the cost, lack of availability of stable isotopes, and the imprecision of mass spectrometry at the time, the use of doubly labeled water (DLW) was limited to small animal studies. In 1982, Schoeller and Van Santen (26) published the first reports of the use of DLW in humans.

The DLW methodology is based on the fact that oxygen in expired carbon dioxide is in isotopic equilibrium with the oxygen in body water (16). A loading dose of water containing deuterium (^2H_2O) and ^{18}O is ingested and allowed to equilibrate with the total body water. Subsequent water lost from the body during normal water turnover contains the two isotopic labels proportional to their concentrations in the body water. However, in addition to the loss as water, the ^{18}O isotope is also lost in the expired CO_2. Therefore, the difference in the rate of loss between the two labels is due to CO_2 production. Using a measured or assumed respiratory quotient and the valued derived for CO_2 production, oxygen consumption can be calculated.

This technique is safe and effective, as the isotopes employed are naturally occurring stable isotopes rather than radioactive isotopes and they are given in minute amounts (15,16,27,35). Recent reports by several investigators have validated the use of DLW in humans during time periods of sedentary and high activity (1,12,14,27,34). When compared with respirometry or direct calorimetry, no systematic bias has been reported. A validation study using the DLW method during rest and exercise in Patas monkeys has recently been completed in our lab. Our results are supportive of the general conclusion that DLW is a valid, effective index of energy expenditure in free-living humans (8). The results from these validation studies has lead to the conclusion that the method is as accurate as respirometry and has a precision of 2–8%, depending on the amount of isotope ingested and rate of isotope turnover (28). It is therefore suggested that the present values for the energy expenditure of this population is a true reflection of the average total daily energy expenditure for these athletes. There does not appear to be a sound basis upon which the negative energy balance can be argued to be due to the overestimation of energy expenditure.

In one of the few well-controlled studies, Mulligan and Butterfield (22) reported mean negative energy balances of 933 $kJ \cdot d^{-1}$ for moderately active runners ($N = 9$) and a mean negative energy balance of 2703 $kJ \cdot d^{-1}$ for very active runners ($N = 7$). Even the non runners ($N = 5$) demonstrated a mean negative energy balance of 176 $kJ \cdot d^{-1}$. Multiple 3-d dietary records, for assessment of energy intake, and physical activity diaries, for measurement of energy expenditure by the factorial method were used to assess energy balance.

Mulligan and Butterfield (22) concluded that there was a demonstrable metabolic efficiency in women that had adapted to high levels of activity, i.e., they could maintain body weight without an appreciable increase in food intake relative to sedentary women. Unfortunately, the factorial method of assessing energy expenditure has been previously reported to have an individual error in determination of daily energy expenditure ranging from −17% to +25% in one investigation and 110% in another report (10,34).

In the present study, Figure 1 illustrates a 32% difference (3914 $kJ \cdot d^{-1}$) in the mean daily values for EE vs EI. There was no change in body weight in these female athletes over the course of the week despite the observed discrepancy in energy balance. Consideration of only these two observations would justifiably lead to the conclusion of a remarkable metabolic efficiency in this group of runners. However, we feel that this purported metabolic efficiency is an incorrect explanation when the rest of our findings are taken into account. First, the positive correlation (r = 0.82) observed, in this study, between EE and body weight is reasonable and to be expected (Fig. 2). Heavier people expend more energy during most physical activities if all other things are equal. Since this is a relatively homogeneous group in terms of habitual physical activity and because they are doing approximately the same amount of training, it is to be expected that the heavier women would expend a greater total number of kilojoules. On the other hand, it is hard to understand or justify the negative correlation (r = −0.74) observed between EI and body weight (Fig. 3) or BMI and EI-EE (r = −0.79; Fig. 4). These findings would suggest that a heavier woman athlete is more metabolically efficient than a lighter woman athlete. The inherent contradiction in these two findings may, perhaps, be best explained by examination of Figure 5. The graph illustrates the negative correlation observed (r = −0.78) between body weight and self-perceived BI. The heavier women do not hold high opinions of their own, perceived, BI. In other words, they are body weight conscious.

Schoeller (29) recently reported that other studies, using the doubly labeled water methodology, have reported 20–30% discrepancies between EI and EE in obese subjects due mainly to a large tendency to under report food intake. Systematic underreporting of food intake can be due to either a failure to report or to undereating during the recording period. Since there was no body weight loss during the week, which would be the consequence of undereating, we believe that the primary source of error, in this study, is underreporting of food intake. Female athletes that perceive they are heavier than either their peers or some athletic "ideal" may be every bit as weight conscious as obese individuals which could lead to a systematic underreporting of food intake on food diaries.

A systematic underreporting of food intake would also explain the confounding relationship observed in this study between energy expenditure and energy intake. Not only was there a mean difference of 32% between EI and EE, there was also a negative correlation observed between these two measures (r = −0.83). The greater the EE measured the lower the EI. This relationship suggests that the greater the number of kilojoules expended the less food energy is taken in. This seems unlikely since it violates the laws of thermodynamics.

Schulz et al. (30) recently published the results of an investigation in which nine female endurance athletes underwent measurement of energy expenditure by a combination of respiratory chamber and doubly labeled water. Over the 6-d metabolic measurement period, energy intakes as estimated by free-living energy expenditure using doubly labeled water plus changes in body energy stores were 925 ± 2300 kJ greater than those calculated from food records. These authors hypothesized an underreporting of food intake and consequently found no good evidence for unusually low energy requirements (30).

Past reports of purported metabolic efficiency in female endurance athletes may be the result of the instruments used and not due to actual hypothesized physiological adaptations. Our results indicate that self-reported food diaries may not be an appropriate instrument in this weight conscious population for the quantification of energy intake and there may be unacceptable levels of error associated with their use. Therefore, we advise caution in the use of these instruments, and further attempts should be made to improve the validity of these important assessment tools.

This study was supported in part by The Athletic Congress, Indianapolis, IN, and a NIH Shared Instrumentation grant no. S10RR07269. The authors wish to thank Phil Henson, Roseann Wilson, Sam Bell, and Harmon Brown for their encouragement and support, Mike Niederpruem for his technical assistance, and all the women runners who kindly participated in this study.

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