Simultaneous measurement of free-living energy expenditure by the doubly labeled water method and heart-rate monitoring[1-3]

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ABSTRACT Total energy expenditure (TEE) was measured simultaneously in 14 free-living adults over 15 d by the doubly labeled water (DLW) method and for 2–4 separate days by heart-rate (HR) monitoring. Individual curves for HR vs oxygen consumption ($\dot{V}O_2$) were obtained and an HR (FLEX HR: 97 ± 8 beats/min, range 84–113 beats/min) that discriminated between rest and activity was identified. Calibration curves were used to assign an energy value to daytime HR above FLEX HR. Below FLEX HR energy expenditure was taken as resting metabolism. Sleeping energy expenditure was assumed to be equal to basal metabolic rate. Average HR TEE (12.99 ± 3.83 MJ/d) and average DLW TEE (12.89 ± 3.80 MJ/d) were similar. HR TEE discrepancies ranged from −22.2% to +52.1%, with nine values lying within ±10% of DLW TEE estimates. The FLEX HR method provides a close estimation of the TEE of population groups. However, an increased number of sampling days may improve the precision of individual estimates of TEE. *Am J Clin Nutr* 1990;52:59–65.

KEY WORDS Energy expenditure, doubly labeled water method, heart rate, free-living adults

Introduction

Habitual energy expenditure (1–4) and activity patterns (5–7) have been investigated with a variety of methods. However, in most cases, because of imposed restrictions on lifestyle and the length of time over which subjects can reasonably be expected to cooperate, the results are of doubtful validity and the methods are of limited applicability in population studies.

Currently the doubly labeled water ($^2H_2{}^{18}O$) method (DLW) and heart-rate (HR) monitoring are two of the most socially acceptable and objective methods for estimating total energy expenditure (TEE). Moreover they can be applied for periods long enough to provide representative estimates of energy turnover.

Whereas the DLW method is now an accepted field technique, HR methodology remains controversial and problematic (8). The relationship between HR and oxygen consumption ($\dot{V}O_2$), while unique to each individual, is normally described as linear at energy expenditures above basal and below maximal output. Previous studies in evaluating HR-$\dot{V}O_2$ methodology derived a TEE value from the average daily HR by fitting one linear or two linear or curvilinear relationships to the data (3, 9–11).

These differences in interpretation have been attempts to circumvent the poor predictive power of HR monitoring as an index of energy expenditure at low levels of activity, particularly in the critical HR range where resting and active conditions converge and overlap. Because the mean daily HR will lie within this critical range in most cases, simultaneous measurements of 24-h TEE in this way have compared unfavorably with other field techniques (3) assumed to be more accurate and with whole-body calorimetry (10).

In this study individual HR vs $\dot{V}O_2$ calibration curves were obtained and an HR (FLEX HR) that discriminated between resting and exercise HR was identified. The calibration curves were used to assign an energy value to minute-by-minute recorded HR above the predetermined FLEX HR. For periods of inactivity when HR cannot be used to predict energy expenditure with any acceptable degree of accuracy, energy turnover is estimated from individually determined values for resting metabolic rate (RMR) (12, 13). In initial validation studies that used whole-body calorimetry as a standard, the average error was 2.7 ± 9.2% (12) and −1.2 ± 6.2% (13), indicating very good predictive power for group estimates of TEE.

The aim of this study is to validate the FLEX HR method in the free-living situation by comparing results of HR TEE with results from simultaneous measurement of TEE by the DLW method.

Subjects and methods

Subjects

Fourteen subjects (nine males, five females) took part in the current study. The subjects were part of a larger cohort of 32

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subjects (16 males, 16 females) who had participated in a study involving simultaneous measurement of TEE by the DLW method and food intake by the 7-d weighed inventory technique. All subjects had previously cooperated in the Northern Ireland Diet and Health Study (14) and were selected to represent a range of energy intakes as assessed in that study by the 7-d weighed inventory technique. Recruitment was by letter and follow-up interview with each subject. Ethical approval for the study was obtained from the Queen's University Ethical Committee, Belfast, Northern Ireland.

Basal metabolic rate

Basal metabolic rate (BMR) was measured under standard conditions in a comfortably warm room, with the subject lying at complete rest and having fasted for 13 h. Immediately after the subject awoke, respiratory gas-exchange rates were measured at 1-min intervals for 40 min with a Mijnhardt Oxycon-4/Apple II Computer Test System interfaced with a dry-gas-meter paramagnetic oxygen analyzer, infrared carbon dioxide analyzer and electronic microprocessor system (Cardiokinetics Ltd, Medical Diagnostic Instrumentation, Salford, UK). Expired air was collected with a two-way nonrebreathing valve and noseclip (Hans Rudolph Inc, Kansas City, MO). Gas analyzers were calibrated before each measurement period with standard gases. Data for the first 5 min were discarded to clear the system of room air. On the evening before measurements were made, each subject was familiarized with the equipment and the technique. Gas volumes were corrected to standard temperature and pressure (STPD) and energy values were determined from oxygen consumption using the Weir formula (15).

The doubly labeled water method

After a predose urine sample was collected, each subject was dosed orally with 0.05 g ^2H_2O and 0.15 g $H_2{}^{18}O$/kg body wt and refrained from eating and drinking for a 4-h equilibration period. Samples were collected of all urine passed during the 24 h after dosing, and a single sample was collected midmorning on each of the next 14 d. Isotope enrichments of pre- and postdose urine samples were measured relative to a local standard by isotope-ratio mass spectrometry (Aqua-Sira model, VG IsoGas, Cheshire, UK). Isotope enrichments of postdose urine samples were corrected for natural background amounts by subtracting the subject's mean enrichment values from the respective predose urine sample. Each measurement was made in duplicate.

Rate constants for isotope disappearance (K_o and K_d for ^{18}O and ^2H, respectively) and isotope distribution volumes (V_o and V_d) were calculated from monoexponential curves fitted to the isotopic data (16). Corrections for isotope fractionation in respiratory and perspiratory water loss were made by assuming that the equivalence of respiratory water loss to carbon dioxide production was 1.027 mol H_2O/mol CO_2 and that 27.8 mol H_2O/d was subject to fractionation as insensible loss through the skin. Factors of 0.93 and 0.99, respectively, were applied for ^2H and ^{18}O fractionation in these losses. For ^{18}O fractionation in carbon dioxide output, a value of 1.04 was used. The origin and biological significance of these values are fully discussed elsewhere (4). When these assumptions are made, carbon dioxide output (F_{CO_2}) expressed as mol/d is derived from the following equation:

$$F_{CO_2} = \frac{K_o V_o - K_d V_d - 27.8\,(0.99 - 0.93)}{2\,(1.04) + 1.027\,(0.99 - 0.93)}$$

where K_o and K_d are per day and V_o and V_d are moles of water. For this group of subjects, the proportions of total water loss to which fractionation corrections was in effect applied were 29 ± 5% and 32 ± 6% for males and females, respectively.

During the isotope-measurement period, each subject kept a 7-d weighed record of all food and fluids consumed. Nutrient content and food quotients were calculated from food tables (17). The mean respiratory quotient (RQ) required for the estimation of energy expenditure from carbon dioxide was calculated from measured food quotients (18).

Standard errors of the individual 15-d estimates were calculated from the observed standard errors of K_o, K_d, V_o, and V_d and were 6.0 ± 2.6% (16). Further details of the method are described elsewhere (4, 16).

Individual heart-rate energy-expenditure regression equations

The procedures applied in this study for the derivation of calibration curves, identification of the FLEX HR threshold, and estimation of 24-h TEE were adopted from those fully described elsewhere (13). To determine the individual HR-$\dot{V}O_2$ regression line, five calibration points were obtained by simultaneous measurement of $\dot{V}O_2$ and recording of HR under standardized conditions. Subjects were instructed to avoid strenuous physical activity on the day of the experiment. Calibrations were carried out at least 2 h postprandially and after the subject had rested for 30 min after arriving at the laboratory. Calibration points were obtained for the following activities carried out in sequence: lying in the supine position, sitting quietly, standing quietly, stepping at 25 steps/min on a 22.5-cm block, exercising at a workload of 9.8 N at 50 rpm on a bicycle ergometer. A metronome was used to achieve steady-state conditions for the stepping and cycling exercises.

A 5-min period was allowed for HR and breathing to stabilize between each of the resting activities and 10 min was allowed between the stepping and cycling exercises. A preliminary equilibration period of 3 min was allowed for each activity, followed by a 3-min sampling period. HR was recorded continuously before and during the whole period of respiratory gas collections. Energy values were determined from $\dot{V}O_2$ as previously described. The calibration point for each activity was computed as the mean of the HR and $\dot{V}O_2$ values for the 3-min sampling period.

Heart-rate monitoring

HR was monitored in the laboratory and in free-living situations with a cardiofrequency meter (Sport Tester PE 3000, Polar Electro, Kempele, Finland). The system consists of an electrode-belt transmitter and wrist microcomputer receiver that stores the pulse in a memory. Pulse was recorded at 1-min intervals up to a maximum recording time of 16 h, when stored information was retrieved and the memory reprogrammed. Information was retrieved via an interface unit and microcomputer for which an additional program was written to compute TEE from HR. The objective was to obtain three or four representative estimates of 24-h energy expenditure during the isotope-measurement period. Sampling days included 2 work (week) days and 2 rest (weekend) days. Each subject was fitted with the HR instrumentation early in the morning; it was worn for 16 h until it was removed by the subject late in the evening. One drawback encountered with the HR monitors was that electrode belts occasionally came loose as subjects followed their normal daily activities, resulting in lost transmissions. However, the protocol was well accepted by the subjects except for 2 subjects who experienced minor skin irritations, and 12 subjects produced three or more 16-h recordings each.

Subjects were instructed to complete a daily record of the nature and approximate duration of all activities during the sampling periods. Detailed records were not asked for because it was felt that this imposition would interfere with habitual physical-activity patterns. An interview questionnaire was administered to assess habitual physical-activity patterns in occupational and discretionary activities.

Calculation of 24-h energy expenditure from heart-rate monitoring

FLEX HR was calculated as the mean of the highest HR for the standing activity and the lowest HR of the exercise activities. RMR was calculated as the mean of the $\dot{V}O_2$ for the resting activities (lying, sitting, and standing). Energy expenditure for the 16 h of HR monitoring was determined as follows. Energy expenditure for periods of time when the HR fell below the FLEX HR was calculated as RMR. For the remainder of the time, when HR was above FLEX HR energy expenditure was derived from the minute-by-minute recorded HR by reference to the subject's regression line for the $\dot{V}O_2$ corresponding to the HR. Twenty-four–hour energy expenditure was computed by summing the estimated energy expenditure by HR monitoring and energy expenditure at night. The latter was assumed to be equal to the measured BMR.

Statistical analysis

Values in the text and tables are expressed as the mean and SD and in the figures as mean and SEM. Dispersion between distributions is expressed as the coefficient of variation (CV). Agreement between the two methods was assessed with the method of Bland and Altman (19). This requires that the difference between the test and reference values be plotted against the mean of the two estimates for each individual. Otherwise statistical analysis was performed using paired t tests and Pearson correlation coefficients (20). Values were considered significant at $p < 0.05$.

Results

The occupational and physical characteristics of the subjects are shown in **Table 1.** All subjects were nonsmokers and were not taking any drugs or medication that might influence metabolism. None of the female subjects was taking oral contraceptives and none was pregnant. Only one female subject (subject 10) was lactating (18 mo postpartum).

The cohort included a wide range of full- and parttime occupations, socioeconomic groups, ages, and body weights. One male subject (subject 1) was in full-time manual employment. The occupational demands of subjects 3, 7, and 10 included a manual component but otherwise the majority of occupations involved predominantly sedentary activity.

Only one subject (subject 2) did not undertake regular physical recreation. Many of the subjects were regular participants in medium-to-high intensity sports activities, such as football, jogging, karate, and volleyball for male subjects and badminton, swimming, cycling, and keeping fit for female subjects.

Interindividual variation in resting pulse rate, body weight, and state of physical training is reflected in the range of slopes and intercepts for the calibration regression equations. The average slope of 0.59 ± 0.12 $kJ \cdot min^{-1} \cdot beat^{-1}$ (range 0.40–0.72 $kJ \cdot min^{-1} \cdot beat^{-1}$) for the male subjects was steeper ($p < 0.01$) than the corresponding value of 0.41 ± 0.05 $kJ \cdot min^{-1} \cdot beat^{-1}$ (range 0.31–0.47 $kJ \cdot min^{-1} \cdot beat^{-1}$) for the female subjects. Intercept values ranged from −50.2 to −19.6 kJ/min for the males and from −40.3 to −20.2 kJ/min for the females but the mean intercept values (males, 11.4 kJ/min; females, 7.0 kJ/min) were not significantly different. Correlation coefficients for all calibrations were high, averaging 0.976 ± 0.014 for the sample, with no correlation being < 0.950. Similarly, as shown in **Table 2,** there was a wide variation in the FLEX HR thresholds of the subjects (male range, 84–113 beats/min; female range, 98–105 beats/min) but the difference between the mean FLEX HR points of the females (102 ± 3 beats/min) and males (95 ± 9 beats/min) was not significant. Mean daytime HR of the females (93 ± 3 beats/min) was also correspondingly higher than that of the male subjects (87 ± 9 beats/min).

The results for estimated TEE by the DLW method and HR monitoring are compared in **Table 3.** On average the HR method overestimated TEE by $+2.0 \pm 17.9\%$ (paired $t = +0.15$, NS). In male subjects there was an overestimation of HR TEE ($+5.3 \pm 20.6\%$) and in female subjects there was an underestimation ($-4.0 \pm 11.5\%$). Although individual discrepancies ranged from −22.2% to +52.1% (−4.81 to +6.77 MJ/d) in nine subjects (six males, three females), the values lay within ±10% of DLW estimates.

The degree of agreement between DLW and HR TEE was assessed by comparing the difference between the two methods with their mean (**Figure 1**) (19). The 95% confidence interval for the bias was −1.37 to +1.57 MJ/d ($t = 0.5$; NS). The 95% confidence limits (mean difference in TEE ± 2SD) were −5.0 to +5.19 MJ/d. If the two subjects (subjects 1 and 8) whose HR TEE was −22.2% and +52.1%, respectively, of DLW TEE are excluded from the data, the corresponding 95% confidence interval for the bias is −0.79 to +0.71 MJ/d and the 95% confidence limits are −2.40 to 2.31 MJ/d.

Figure 2 shows the partitioning of TEE estimated by the FLEX HR method into the three components used in its calculation: BMR, RMR, and physical activity above FLEX HR. The mean values for the ratio of RMR to BMR, which reflect the energy cost of sedentary activity, were 1.30 ± 0.07 for males and 1.33 ± 0.06 for the females. In absolute terms sedentary energy expenditure was 2.29 ± 0.55 MJ/d for males and 1.88 ± 0.45 MJ/d for females. The physical-activity index (PAI), which is expressed as the ratio of TEE to BMR, provides a measure of activity that is independent of body weight, sex, and age because these confounding factors will be expressed in the BMR estimates.

The values for PAI were highly correlated ($r = +0.947$) with the range of observed daytime HR above FLEX HR thresholds (**Figs 3 and 4**). In these subjects the range varied from 0.5 to 7 h and clearly reflected the extremes of physical-activity patterns of the cohort. The mean PAI values were 1.99 ± 0.44, range 1.39–2.73, for the males and 1.63 ± 0.05, range 1.56–1.69, for the females. When expressed in absolute terms (TEE − BMR)

TABLE 1
Description of subjects

Occupation	Age	Height	Weight	Percent ideal body weight*
	y	*m*	*kg*	*%*
Male subjects				
1 Construction laborer	32	1.79	88.2	124
2 Policeman	25	1.80	111.4	155
3 Retail manager	28	1.77	77.5	111
4 Clerical officer	32	1.74	76.5	112
5 Sales executive	41	1.67	65.5	101
6 Architectural technician	30	1.93	79.1	97
7 Fireman	32	1.75	81.8	119
8 Full-time student	17	1.72	67.3	102
9 Policeman	28	1.82	90.0	123
$\bar{x} \pm SD$	29.4 ± 6.4	1.78 ± 0.07	81.9 ± 13.8	116 ± 18
Female subjects				
10 Clinical teacher	28	1.67	59.5	98
11 Company cashier	46	1.64	68.2	116
12 Part-time librarian	31	1.53	53.6	100
13 Housewife	34	1.60	46.8	82
14 Housewife	32	1.66	63.6	105
$\bar{x} \pm SD$	34.2 ± 6.9	1.62 ± 0.06	58.3 ± 8.4	100 ± 12

* Midpoint of the weight range for medium frame size (21).

there was an approximately fivefold range in the energy turnover in physical activity between the subjects (2.69–12.54 MJ/d, CV 51%).

Figure 4 illustrates the percentage of time during the daytime that HR was above the FLEX HR and at FLEX HR ± 5 heartbeats. Because the predictive power of the method may be poorest in the FLEX HR ± 5 heartbeat range (~80–115 beats/min for this group) because of an overlap in resting and exercise HR, the errors in estimating HR TEE may increase relative to the amount of time that HR is within this range. In this group the amount of daytime HR spent at FLEX HR ± 5 heartbeats ranged from 0.5 h for a very inactive subject (subject 5) to 4 h for a subject (subject 1) employed in heavy manual work. In the majority of subjects an approximately equivalent or greater

TABLE 2
Estimation of mean 24-h energy expenditure (TEE) by the FLEX heart-rate (HR) method

Subject	Days sampled	Mean TEE	Coefficient of variation	FLEX HR	Daytime HR Mean	Daytime HR Range
	n	*MJ/d*	*%*	*beats/min*	*beats/min*	
1	3	16.90	26	99	92	60–151
2	3	14.10	5	113	90	66–127
3	2	16.75	16	84	80	42–160
4	4	12.55	26	92	82	53–147
5	4	9.53	6	90	78	57–132
6	3	16.77	3	99	94	58–163
7	3	16.38	33	94	84	54–171
8	3	19.77	11	100	105	70–169
9	2	13.19	30	86	75	46–124
10	3	10.16	9	98	88	56–149
11	3	9.74	15	101	95	60–154
12	3	8.17	8	105	94	63–140
13	3	8.18	11	100	91	62–153
14	3	9.69	7	104	96	74–154
Males*	3 ± 0	15.10 ± 3.05	17 ± 12	95 ± 9	87 ± 9	
Females*	3 ± 0	9.19 ± 0.94	10 ± 3	102 ± 3	93 ± 3	
All subjects*	3 ± 0.6	12.99 ± 3.83	15 ± 10	97 ± 8	89 ± 8	

* $\bar{x} \pm SD$.

TABLE 3
Total energy expenditure (TEE) estimated by doubly labeled water (DLW) and heart-rate (HR) monitoring

Subject	DLW TEE	HR TEE	Percent difference*
	MJ/d	*MJ/d*	%
1	21.71	16.90	−22.2
2	15.69	14.10	−10.1
3	16.52	16.75	+1.4
4	11.17	12.55	+12.4
5	9.87	9.53	−3.4
6	15.24	16.77	+10.0
7	15.18	16.38	+7.9
8	13.00	19.77	+52.1
9	13.16	13.19	0.0
10	11.97	10.16	−15.1
11	11.18	9.74	−12.9
12	7.59	8.17	+7.6
13	7.51	8.18	+8.9
14	10.60	9.69	−8.6
Males†	14.62 ± 3.44	15.10 ± 3.05	+5.3 ± 20.6
Females†	9.77 ± 2.08	9.19 ± 0.94	−4.0 ± 11.5
All subjects†	12.89 ± 3.80	12.99 ± 3.83	+2.0 ± 17.9

* Percent difference = [(HR − DLW)/DLW] × 100.
† $\bar{x}$ ± SD.

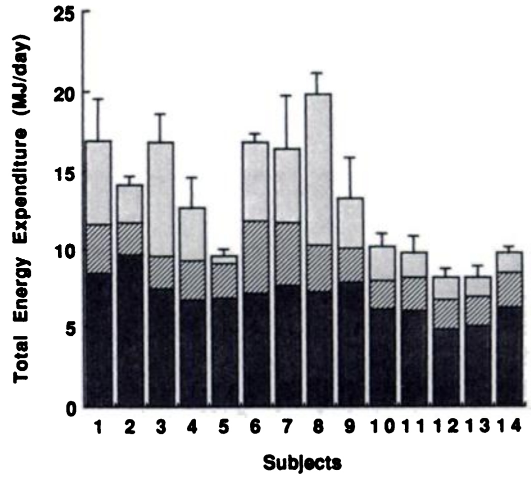

FIG 2. Partitioning of total energy expenditure estimated by the FLEX HR method. ■ Sleep (BMR), ▨ sedentary periods (RMR), □ activity predicted from HR above FLEX HR.

amount of time (1.5–4 h/d) was spent at FLEX HR ± 5 heartbeats than actually above FLEX HR. In contrast the sustained submaximal activity of subjects 3 and 8 resulted in 2 h of daytime HR at FLEX HR ± 5 but between 5 and 7 h of HR above the FLEX HR threshold.

Discussion

Currently the DLW method is the most accurate method of providing an integrated and representative estimate of TEE in the unencumbered individual, but its application in large-scale population studies is prohibited by its cost. Moreover, in epidemiological investigations it may not even be the most appropriate procedure to apply, particularly if the purpose is to evaluate intraindividual variability in patterns of physical activity and energy expenditure. In these circumstances the application of less sophisticated, more cost effective, and appropriately validated methodology such as HR monitoring is indicated.

In free-living subjects the precision obtained by the FLEX HR method will be contingent upon the habitual physical-activity patterns of the subjects in relation to their defined threshold HR. The mean daytime HR, the wide variation in HR with time, and interindividual spread in derived PAI values of these subjects suggest that their lifestyles are dictated by largely sedentary occupations interspersed with bouts of discretionary and/or occupational activity of varying intensity. As such the

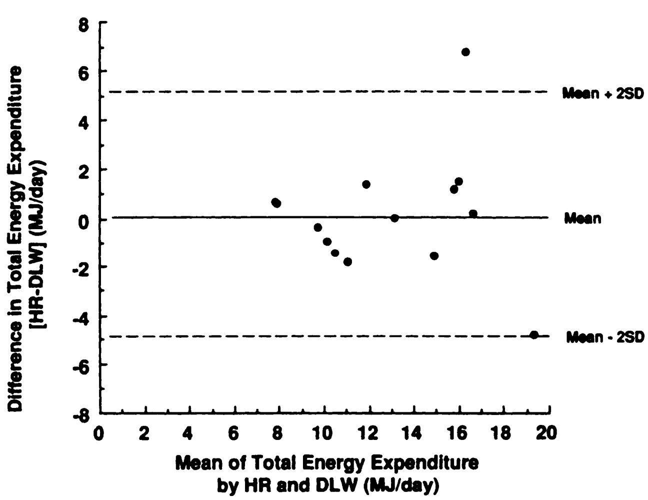

FIG 1. Difference in energy expenditure vs mean of energy expenditure for DLW and HR data.

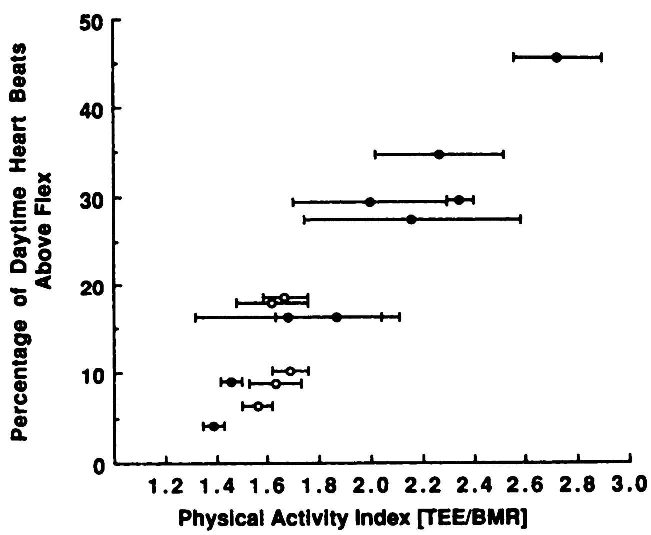

FIG 3. Relationship between physical activity index (TEE:BMR) and percentage of time during the daytime when heart beats were above FLEX HR (r = +0.947, n = 14). ● Males, ○ Females.

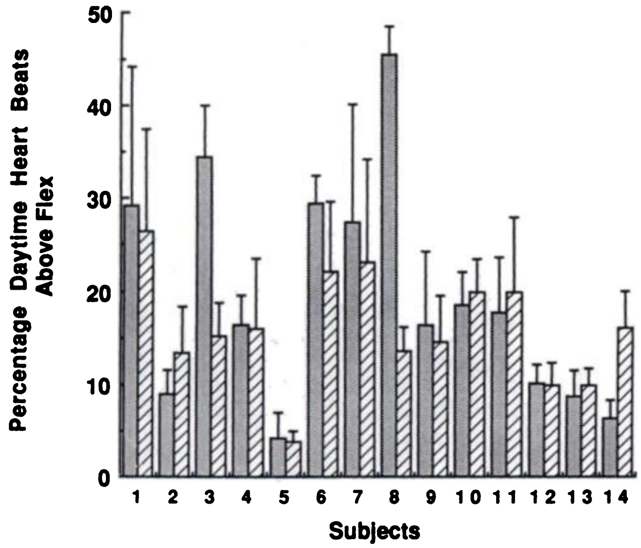

FIG 4. Percentage of time during the daytime when heart beats were above FLEX HR (□) and at FLEX HR ± 5 heartbeats (▨).

cohort could be assumed to provide a suitably broad spectrum of habitual physical activity with which to assess the validity of the method in free-living conditions.

In very sedentary subjects the precision of the estimate will be heavily dependent on the accuracy of the RMR values because in these cases the mean daytime HR does not closely approximate the FLEX and, more importantly, relatively little daytime HR is spent around or above the FLEX HR. Under field conditions the derived RMRs of these subjects (males, $1.30 \pm 0.08 \times$ BMR; females, $1.33 \pm 0.06 \times$ BMR) lie between theoretically estimated survival ($1.27 \times$ BMR) and maintenance requirements ($1.4 \times$ BMR) (22) and are compatible with 24-h whole-body calorimetry computations of BMR (13). Determinations of RMR from relatively short calibration procedures therefore appear to be no less accurate than those derived from more precise methodology and provide a valid estimate of the energy cost of a sedentary existence. Consequently in very inactive subjects, for example subject 5, a reliable measure of TEE is likely to be obtained from derived RMR values plus a small increment for physical activity predicted from HR above FLEX.

The principal challenge to the integrity of the method lies in predicting the energy expenditure of mainly sedentary occupational activity with intermittent episodes of physical activity of varying intensity as was the case in the majority of the cohort. As a result ~1.5–4 h of daytime HR (Fig 4) was spent in the range FLEX HR ± 5 where the ability to predict energy expenditure from HR and/or RMR is poorest because of the overlap in resting and exercise HR. Then the definition of an appropriate FLEX HR will be a major factor in determining the predictive power of the method. However, possible errors in definition would still only partially explain the observed discrepancies in TEE values estimated from DLW and HR. For example, reanalysis of the data for subjects 10 and 11 indicates that FLEX HR values should have been +10 and −8 heartbeats, respectively, from those predicted to account for the observed TEE differences. Prediction errors in FLEX HR definition of this order of magnitude seem unlikely. Moreover, this explanation is based on the tenuous assumption that one discrete pulse point can provide a clear-cut physiological distinction between rest and exercise HR. Rather, it is in the critical FLEX HR ± 5 range where any major errors in FLEX HR definition will be compounded by unquantifiable cardiovascular responses to confounding physiological variables, such as the site, kind, and intensity of muscle activity; posture; fatigue; and prandial status.

At the other extreme of physical-activity status as observed in subjects 3 and 8, when relatively little daytime HR is spent in the range FLEX HR ± 5 heartbeats compared with the proportion of time clearly above FLEX HR, prediction errors will be dependent not only on the appropriateness of the FLEX point but also on the derived regression lines. Methodological errors in one or both of these factors are likely to have contributed to the very large overestimate in HR TEE observed in subject 8. However, situational factors cannot be ruled out because the school vacation and the novelty of HR monitoring resulted in an overspill of youthful enthusiasm and energy expenditure. The subject's diary, which recorded atypically lengthy periods of physical exercise, supports this contention.

Another potential source of error in HR estimates of TEE is the need to assume an energy value for sleep equivalent to the BMR. Metabolic rate during sleep has been shown to be ~10% lower than standardized measurements of BMR, which would introduce an average overestimate of ~5% during the sleeping period (23). In any case because the energy cost of sleep is so low, integrating it into estimated TEE values over 24 h would only result in an average error of 1.6%. Because direct measurements of BMR were applied in this study, the error involved is likely to be insignificant and did not warrant including a correction factor to account for this. However, in large-scale community studies the only feasible alternative may be the estimation of sleeping metabolic rate from predicted BMR values, which have an apparent accuracy of precision of at best ±10% (24). In these circumstances individual errors in calculating the energy turnover in sleep are likely to be greater. However, relative to the errors in predicting daytime energy expenditure, their overall significance may not be large.

Although part of the observed individual discrepancies in TEE estimated from DLW and HR are undoubtedly due to inherent errors in measurement, they could also be partly attributed to the sampling times of the methodologies. The more representative medium-term observations of the DLW method and the significant spread of intraindividual variation in HR TEE suggest that in some cases the sampling periods may have been inappropriately too short to provide reproducible data. For example, the energy expenditure of subject 1 was measured over 1 very inactive day, 1 d equally divided between occupational and nonoccupational activity, and 1 d of intensive occupational activity resulting in a CV of 26% and a −22.2% (−4.81 MJ/d) difference in estimated TEE by the two methods. In part this discrepancy can be explained by the nature of the occupational activity of this subject in which increased cardiac output and stroke volume caused by repetitive patterns of stooping, bending, and straightening up may have resulted in a relative increase in oxygen consumption over HR. However it may also be due to unrepresentative sampling, because a weighted average based on his habitual physical activity pattern of 12-h work shifts for 6 d/wk would predict a HR TEE of 20.65 MJ/d and a discrepancy of −4.7% between HR and DLW estimates of TEE.

The definition of a reproducible FLEX HR value is clearly one of the most problematic features of the technique and in field situations may present additional problems to those encountered under whole-body-calorimetry conditions. In the first place it is evident that no matter how meticulously calibration procedures are performed, it is most unlikely that HR changes in these necessarily contrived situations can duplicate the cardiorespiratory dynamics associated with spontaneous and complex free-living energy-expenditure patterns. Precision is likely to be improved if calibration procedures embrace the usual gamut of activities of the subject. However, the feasibility of doing so in community studies will depend on the facilities available for measuring respiratory gas exchange and the homogeneity or heterogeneity of habitual physical-activity patterns. Moreover, it is conceivable that unphysiological breathing with facemasks or mouthpieces and noseclips could result in a stress-induced tachycardia and mask FLEX HR definition. Although procedures for the prediction of the FLEX HR other than the one adopted in this study have been discussed (12, 13), prediction of FLEX HR remains one of the major potential sources of error in field applications of the method and one that is not easily overcome.

In conclusion, no single field method of measuring energy expenditure will address all the questions raised in estimating and evaluating free-living energy requirements. In this respect the FLEX HR method can make its own contribution. Although individual estimates of TEE may be subject to unacceptable error, this should not preclude use of the method in population studies where its simplicity, objectivity, social acceptability, and ease of data processing all favor its application. Furthermore, by dissociating the components of TEE, it is the first field technique to provide objective indices of habitual physical-activity patterns and associated cardiorespiratory function. Therefore, its potential in epidemiological studies for assessing the efficacy of physical activity in the maintenance of health and development of disease is obvious.

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