# Energy expenditure from minute-by-minute heart-rate recording: comparison with indirect calorimetry[1-3]

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**ABSTRACT** Total daily energy expenditure (TDEE) and energy expended in activity (EAC) were estimated by the minute-by-minute heart-rate method in 22 (16 men, 6 women) individually calibrated subjects and compared with values obtained by whole-body indirect calorimetry. Subjects followed four activity protocols during the 22 h in the calorimeter; no exercise ($n = 6$) and 2 ($n = 5$), 4 ($n = 4$), and 6 ($n = 6$) 30-min bouts of exercise on a bicycle ergometer at varying intensities. There were no statistically significant differences between the two methods in TDEE or EAC in any of the sex or protocol groupings. The regression of TDEE by heart rate on TDEE in the calorimeter was $y = 0.92x + 1.0$ MJ; ($r = 0.87$, SEE = 0.91 MJ). The heart-rate method also follows the varying activity patterns of individuals and can be used to closely estimate the TDEE and EAC of even small ($n = 4$–6) groups of subjects. In the present measurements, it gave a maximum error of TDEE for individuals of +20% and −15%. *Am J Clin Nutr* 1988;48:552–9.

**KEY WORDS** Energy expenditure, heart rate, physical activity, oxygen consumption, rest

## Introduction

Attempts to assess the physical activity or daily energy expenditure of individuals or communities have included the factorial method (1), questionnaires (2, 3), pedometers or actometers (4–6), heart-rate accumulators (7–9), and the doubly labeled water technique (10, 11). At the moment the latter seems to be the most widely accepted for accuracy in determining total daily energy expenditure in free-ranging subjects. The two disadvantages of the method are, first, that although it will give accurate measures of average energy expenditure over periods of 10–12 d, it cannot give the pattern(s) of activity and, second, its cost is high both in materials and permanent equipment required for the analyses of the two isotopes. There is a need for a less costly method that can be applied in field situations with reasonable accuracy and that can give some measure of activity pattern(s).

Heart-rate recorders capable of registering and saving heart rates minute by minute without interfering with activity have been developed in a number of laboratories (12–14). The ability to measure heart rate minute by minute and to store the large amount of data collected in a computer for analysis is a distinct advancement over the older heart-rate accumulation method. Because the heart-rate method with all of its potential criticisms is the best practical method for estimating daily energy expenditure in many field situations, its validation against a standard is urgently needed (15). This report provides a comparison of energy expenditures obtained by whole-body indirect calorimetry and minute-by-minute heart-rate recording.

## Subjects and methods

The measurements were carried out at the British MRC Dunn Nutrition Centre in Cambridge with two of the calorimeters in operation there for the indirect measurement of 24-h energy expenditure. Descriptions of these instruments and their use in the rapid calculations of oxygen consumption resulting from changes in activity were presented elsewhere (16, 17). The work described was approved by the Dunn Nutrition Unit Ethical Committee.

### Subjects

The subjects were 16 men (18–66 y) and 6 women (19–47 y). The averages of their physical characteristics are presented

TABLE 1
Physical characteristics of the subjects*

| Variable | Men ($n = 16$) | Women ($n = 6$) |
|---|---|---|
| Age (y) | 31.9 ± 13.0 | 30.2 ± 9.7 |
| Weight (kg) | 68.5 ± 5.7 | 59.4 ± 7.8 |
| Height (m) | 1.746 ± 0.050 | 1.635 ± 0.032 |
| Midupper arm circumference (mm) | 266 ± 20 | 269 ± 24 |
| Sum skinfold measurements (mm) | 27.5 ± 15.3 | 47.3 ± 16.7 ($n = 5$) |

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

in **Table 1**. Body weights (±50 g) were obtained on a CMS beam balance (CMS Weighing Equipment, Ltd, London, UK), thickness of triceps and subscapular and iliac crest skinfold measurements were determined with a Harpenden caliper (Holtain, Ltd, Crymmych, UK) and midarm circumferences were measured with a flexible tape.

### Heart-rate recorder

The device used for recording heart rates was designed and constructed in the Research Service, Zablocki VA Medical Center (by NTC). It is $10 \times 7.5 \times 4$ cm, weighs ~170 g, and thus is easily worn on a belt without interfering with the subject's normal activity. It consists of an analog component for signal conditioning and processing of the ECG signal and a digital section for accumulation of heart beats in 1-min intervals and storage in a 2K random-access memory capable of storing 2048 data points (> 34 h). Three electrodes were placed on the chest (18), two for recording precordial lead CM5 and one for grounding purposes. At the end of the study periods, the heart-rate memories were discharged into a desk-top computer (through a computer interface connected to the RS-232 port) for data storage on diskettes.

### Subject calibration

Each subject was individually calibrated to establish oxygen consumption ($\dot{V}O_2$) and heart-rate (fH) relationship. This was carried out on the afternoon before the subject entered the calorimeter or within the same week of the calorimeter study and occurred at least 2 h after the last meal. Several (four to five) resting values of $\dot{V}O_2$ and fH were obtained with the subject lying, sitting comfortably in a chair, standing, and sitting quietly on the bicycle ergometer (Monark 868, Varberg, Sweden). Measurements were made after 5–10 min rest in each position. The average of all of these measurements was used as the resting energy expenditure (RMR). The subjects then began cycling on the ergometer at 50 cycles/min (metronome) and 0 resistance. Every 3 min the bicycle resistance was elevated by 4.9 N until the subject's heart rate increased to ~150 beats/min. Measurements of fH and $\dot{V}O_2$ were made during the last minute of each 3-min cycling period.

During the calibration procedure $\dot{V}O_2$ was measured by using a mouthpiece connected to a two-way respiratory valve and a Parkinson-Cowan dry gas meter (Model CD4, C Poe Co, Houston, TX) to determine pulmonary ventilation. A Servomex OA137 oxygen analyzer (Croborough, UK) calibrated with fresh air and oxygen-free nitrogen and a dual-beam infrared carbon dioxide analyzer (type 801, PK Morgan, Chatam, UK) calibrated with 5% $CO_2$ (Haldane apparatus; calibrated to ± 0.02%) were used to measure the expiratory fractions of $O_2$

and $CO_2$. Heart rates were taken from an ECG monitor. $\dot{V}O_2$ and $\dot{V}CO_2$ were calculated as described by Consolazio et al (19). Two calibration curves, one male and one female, are shown in **Figure 1**. Despite the high correlation coefficient of the resting values of the male subject TS in Fig 1, the usual values were very much lower as reflected in the mean ± SD of the 22 subjects of 0.24 ± 0.36 in comparison with 0.98 ± 0.05 for the data obtained during exercise.

### Calorimeter protocols

Each calorimeter was equipped with an arm chair, a small desk, a folding bed, toilet facilities, a telephone and an intercom, a television set, and a bicycle ergometer with a metronome for marking cycling frequency. Meals were passed through a double window hatch between the calorimeter and the control room facility. Before the subjects entered the calorimeter the operation and the facilities were explained to them. Each subject also received a written description of the work protocol to be followed. The general calorimeter protocol is shown in **Figure 2**. Before the subjects entered the calorimeter, electrodes for heart-rate recording were attached and the recorder was started. Subjects were sealed in the calorimeter at 1900 and ate their evening meal between 1930 and 2000. The study period then was started at 2000 and continued until 1800 the following evening when the subjects left the calorimeter. Consequently, the data are based on 22 h of heart-rate recording (with the exception of sleep time) and calorimeter measurements.

The subjects followed one of four exercise protocols (Fig 2): I, no exercise; II, two 30-min exercise bouts between 1030 and 1100 and between 1200 and 1230 at 100 W for males and 75 W for females; III, four 30-min exercise bouts, two as in protocol II and two between 1430 and 1500 and between 1600 and 1630 at 50 W for males and 25 W for females; and IV, six exercise bouts, four as in protocol III plus two between 2030 and 2100 and between 2200 and 2230 on the evening of entry into the calorimeter at 75 W for males and 50 W for females.

The exercise procedure consisted of standing quietly for 5 min beside the bicycle before cycling for 30 min at 50 cycles/min at the prescribed work load followed by 10 min of quiet standing by the bike. The nonexercise periods were taken up by reading, writing, watching television, personal care, etc. During the course of the day, detailed notes were maintained of the subject's activities. A night nurse was on duty between 2000
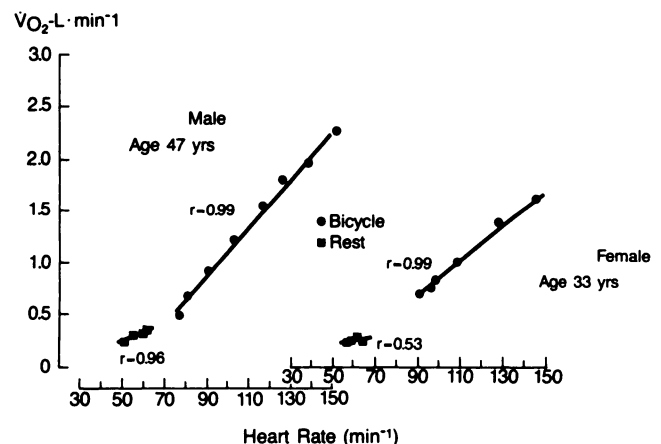


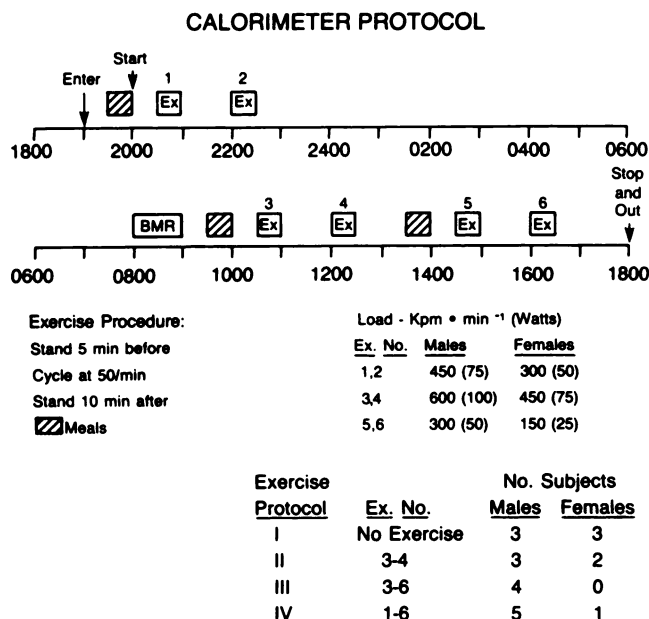FIG 1. Calibration curves of a male subject and a female subject.

FIG 2. Protocol followed by the subjects during 22 h in the calorimeter showing times of meals, bouts of exercise with work loads, and numbers of subjects after each of four protocols. (Kpm = kilopond·m = 9.8 N·m.)

and 0800 to record activity, time of settling down for sleep, etc and to care for the subjects in the event of an emergency. None occurred.

Under field conditions employing the heart-rate method (and in the present experiments), the energy expenditure during sleep is obtained as the product of basal metabolism (BMR) and sleep time. The calorimeter was the instrument used to measure the BMR. In this sense, the calorimeter is the same as any other independent method of indirect calorimetry that might have been used to determine BMR. The subject was awakened gently at 0700 and allowed to go to the toilet if necessary. Shortly before 0800 the subject was again awakened and told to lie quietly and to stay awake for the next hour. Careful monitoring insured that the subject did not fall back asleep. Measurements of $\dot{V}O_2$ and $\dot{V}CO_2$ obtained by the calorimeter during this period were used in calculating BMR with the caloric equivalent for $O_2$ calculated at the measured resiratory quotient as described by Lusk (20).

The measurements made by the calorimeter were calculated as kJ/min and tabulated by the computer at 3-min 20-s intervals during the calorimeter run and at the termination as 30-min averages, as the total energy expenditure during the 22-h study period, and as the average kJ/min during the 1-h BMR period.

At the end of the calorimeter procedure, the heart-rate recorder was detached from the subject and its contents were discharged into the minicomputer together with the times of starting and stopping the calorimeter procedure and of going to sleep and being awakened. Because of malfunction of the heart-rate recorders in two subjects, probably as a result of electrode problems, and the complete detachment of the electrodes in a third subject, the periods of energy expenditure measurements by the heart-rate method and calorimeter were shortened to 20.75, 19, and 16 h, respectively, in these three subjects. However, we refer to the study period as 22 h because all the data analyses are based on comparisons between the two methods.

### Estimation of energy expenditure by the heart-rate method

RMR was calculated as the mean of all the resting values of $\dot{V}O_2$ obtained during the calibration procedure and expressed as kJ/min as described for BMR.

From Figure 1 it is obvious that there are two ranges of heart rates: rest and activity. Consequently, it is necessary to determine a critical heart rate above which the slope and intercept of the calibration curve obtained on the bicycle will be used to calculate $\dot{V}O_2$ and below which RMR will be used to estimate the energy expenditure (EE) for the minute in question. The critical fH is referred to as FHFLEX. Various fH values were tried in the calculation of total daily energy expenditure (TDEE): the average of the highest fH at rest and the lowest during exercise on the bicycle (calculated FHFLEX), the value obtained from looking at the plotted values of $\dot{V}O_2$ on fH (Fig 1, graphed FHFLEX), and a series of values obtained from the calculated FHFLEX +5, +10, +15, and +20 beats/min. The value obtained from looking at the graphed values of $\dot{V}O_2$ on fH was considered too subjective. The other calculated FHFLEX values were then used and empirically (based on a high correlation coefficient [r] and a low standard error of the estimate [SEE] when regression analysis was done of TDEE from heart rate [dependent variable] on the calorimeter TDEE [independent variable]) the value of calculated FHFLEX + 10 was used in the present analysis. Note that the value obtained from calculated FHFLEX + 15 also gave results from TDEE and energy expended in activity (EAC) that were very similar to those reported here. The calculated FHFLEX + 10 is now referred to as FHFLEX. It averaged (±SD) 86 ± 10 beats/min in males and 96 ± 6 beats/min in females and the difference was statistically significant ($p$ = 0.04). There were no statistically significant differences when compared with those values subjectively estimated from the plotted calibration measurements of $\dot{V}O_2$ on fH (85 ± 9 and 94 ± 5, respectively).

The minute-by-minute EE in kJ/min will then be

$$EE = (m \cdot fH + b) \cdot 20.48 \quad \text{at} \quad fH > FHFLEX \quad (1)$$

or

$$EE = RMR \quad \text{at} \quad fH \leq FHFLEX \quad (2)$$

where m is the slope and b is the intercept of the activity calibration line (Fig 1) and RMR is the mean of the resting energy expenditure (REE) values obtained during the calibration procedure before entry into the calorimeter. The time the heart-rate monitoring was used for estimating EE extended from 2000 until the subject settled down to sleep for the night and from the time the subject finished the BMR measurement at 0900 until the subject left the calorimeter at 1800. Consequently, the EE from the monitor (EEM) was

$$EEM = \sum EE \quad (3)$$

during these two periods and the total daily energy expenditure (TDEE) was:

$$TDEE = (ST \cdot BMR) + EEM \quad (4)$$

wherein ST is sleep time in minutes and BMR is in kJ/min. The BMR was measured by the calorimeter and will be the same as the BMR measured by any other appropriate method of indirect calorimetry. It can therefore be considered as independent of the calorimeter. The EE during sleep in the calorimeter determination of TDEE is derived from the individual calorimeter measurements, not from the BMR.

TABLE 2
Total daily energy expenditure (TDEE) and energy expenditure in activity (EAC) as measured by whole body indirect calorimetry and by the heart-rate method*

| Condition | n | TDEE-MJ (kcal) | | EAC-MJ (kcal) | |
|---|---|---|---|---|---|
| | | Calorimeter | Heart rate | Calorimeter | Heart rate |
| Women | 6 | 7.80 ± 1.30 | 8.10 ± 1.46 | 1.47 ± 1.12 | 1.77 ± 1.30 |
| | | (1866 ± 311) | (1938 ± 349) | (352 ± 268) | (423 ± 311) |
| Men | 16 | 10.13 ± 1.39 | 10.34 ± 1.55 | 2.52 ± 1.38 | 2.72 ± 1.50 |
| | | (2423 ± 332) | (2474 ± 371) | (603 ± 330) | (651 ± 359) |
| Protocol I | 6 | 7.37 ± 0.86 | 7.35 ± 0.66 | 0.59 ± 0.36 | 0.57 ± 0.51 |
| | | (1763 ± 206) | (1758 ± 158) | (141 ± 86) | (136 ± 122) |
| Protocol II | 5 | 9.47 ± 0.76 | 9.92 ± 1.25 | 1.98 ± 0.38 | 2.42 ± 0.76 |
| | | (2266 ± 182) | (2373 ± 299) | (474 ± 91) | (579 ± 182) |
| Protocol III | 4 | 10.57 ± 0.54 | 11.29 ± 0.87 | 2.48 ± 0.72 | 3.20 ± 1.35 |
| | | (2529 ± 129) | (2701 ± 208) | (593 ± 172) | (766 ± 323) |
| Protocol IV | 6 | 11.01 ± 1.30 | 10.94 ± 1.00 | 3.86 ± 0.88 | 3.79 ± 0.72 |
| | | (2634 ± 311) | (2617 ± 239) | (923 ± 210) | (907 ± 172) |
| All subjects | 22 | 9.49 ± 1.71 | 9.73 ± 1.81 | 2.23 ± 1.37 | 2.46 ± 1.48 |
| | | (2270 ± 409) | (2328 ± 433) | (533 ± 328) | (588 ± 354) |

* $\bar{x} \pm$ SD. There are no statistically significant differences between the two methods in any of the data groupings.

The energy for body maintenance (MEE) is then

$$MEE = (ST \cdot BMR) + [(1440 - ST) \cdot RMR] \quad (5)$$

where BMR and RMR are both measurements made independently of the calorimeter and expressed in kJ/min. The energy expended in activities (EAC) is then

$$EAC = TDEE - MEE \quad (6)$$

These calculations of MEE and EAC are the same as those presented by Spady (8).

### Statistical analyses

The statistical analyses were carried out on the basis of paired sample $t$ comparisons of the two methods, $F$ ratio comparisons of standard deviations by the two methods, unpaired $t$ comparisons of groups, and least-squares regression analysis with the data from the calorimeter treated as the independent variable (21). The null hypothesis was rejected at the 0.05 level. Throughout the text and in the tables data are presented as means ± SDs.

## Results

The calibration curves of the two sexes exhibit some differences that deserve mention. In these subjects there were no statistically significant differences in the slopes or intercepts of the low activity (resting) values between males and females although the averages of the resting values of EE (RMR) in the two groups (6.7 ± 0.6 and 5.3 ± 0.2 kJ/min [1.6 ± 0.14 and 1.3 ± 0.05 kcal/min], respectively) were significantly different ($p < 0.001$). Also, the average slopes of the curves on the bicycle ergometer were significantly higher in males than in females ($p < 0.001$).

The results of the EEs of the various groupings of subjects are shown in **Table 2**. The data are presented as total daily energy expenditure (TDEE) and that spent in activity (EAC) over and above maintenance energy expenditure. The subject whose electrodes became detached had been assigned to protocol IV. Because of the accident and the fact that three of his assigned six exercise periods were lost, his data were not used in the means for this protocol. There are no statistically significant differences in any of the paired $t$ comparisons between the two methods. Individual values for TDEE and EAC by the two methods are presented in **Table 3**.

The differences between TDEEs measured by calorimeter (Cal) and by heart rate are equal to the differences between EACs for the two methods because MEE is measured independently. Thus,

$$EAC (Cal) = TDEE (Cal) - MEE \quad (7)$$

and

$$EAC (fH) = TDEE (fH) - MEE \quad (8)$$

Because MEE is common to both equations, it can be shown that

$$TDEE (fH) - TDEE (Cal)$$
$$= EAC (fH) - EAC (Cal) \quad (9)$$

When the calorimeter values were subtracted from those obtained by the heart-rate method, the differences varied from −1.86 MJ (−445 kcal) to +1.99 MJ (+476 kcal) in all 22 subjects. As can be seen from Table 2, the mean difference was 0.24 MJ (57 kcal).

An $F$-ratio comparison of the SDs obtained in the two methods revealed no statistically significant differences for either TDEE or EAC in each of the seven groupings shown (Table 2). Thus, the heart-rate method does not show a greater variation in these measurements than that obtained from the calorimeter.

A regression of TDEE by the heart-rate method on the

**TABLE 3**
Individual values of total daily energy expenditure (TDEE) and energy expenditure in activity (EAC) by calorimeter and by the heart-rate method in a 22-h period

| Subject | | | | TDEE-MJ (kcal) | | EAC-MJ (kcal) | |
|---|---|---|---|---|---|---|---|
| Number | Age | Sex | Protocol | Calorimeter | Heart rate | Calorimeter | Heart rate |
| 1 | 33 | M | 4 | 10.57 (2529) | 12.10 (2895) | 2.96 (708) | 4.49 (1073) |
| 2 | 47 | M | 3 | 10.68 (2554) | 12.35 (2955) | 3.28 (785) | 4.96 (1186) |
| 3 | 22 | M | 2 | 9.74 (2330) | 11.73 (2807) | 1.39 (333) | 3.38 (810) |
| 4 | 29 | M | 3 | 11.25 (2692) | 11.40 (2728) | 2.31 (553) | 2.46 (589) |
| 5 | 19 | F | 1 | 7.51 (1797) | 6.71 (1606) | 0.99 (238) | 0.19 (46) |
| 6 | 23 | F | 2 | 8.68 (2076) | 8.22 (1967) | 2.38 (570) | 1.93 (461) |
| 7 | 30 | M | 1 | 7.84 (1876) | 7.09 (1696) | 0.80 (192) | 0.05 (13) |
| 8 | 20 | M | 3 | 9.95 (2381) | 10.23 (2447) | 1.59 (380) | 1.86 (446) |
| 9 | 31 | F | 1 | 6.39 (1528) | 7.01 (1678) | 0.49 (118) | 1.12 (267) |
| 10 | 28 | F | 2 | 8.64 (2068) | 9.80 (2345) | 1.92 (460) | 3.08 (737) |
| 11 | 28 | M | 2 | 10.26 (2454) | 9.68 (2315) | 2.22 (532) | 1.64 (393) |
| 12* | 32 | M | 4 | 10.25 (2453) | 10.39 (2486) | 3.64 (846) | 3.67 (879) |
| 13 | 33 | M | 4 | 12.64 (3025) | 10.78 (2580) | 4.70 (1124) | 2.84 (679) |
| 14 | 47 | F | 1 | 6.23 (1490) | 6.94 (1662) | 0.10 (24) | 0.82 (196) |
| 15 | 46 | M | 1 | 8.16 (1952) | 8.40 (2009) | 0.88 (211) | 1.12 (268) |
| 16 | 43 | M | 4 | 12.50 (2990) | 12.25 (2931) | 5.03 (1203) | 4.78 (1143) |
| 17 | 23 | M | 1 | 8.09 (1936) | 7.94 (1901) | 0.27 (64) | 0.12 (29) |
| 18 | 19 | M | 2 | 10.04 (2403) | 10.15 (2429) | 1.97 (472) | 2.08 (498) |
| 19† | 18 | M | 3 | 10.40 (2488) | 11.16 (2670) | 2.74 (657) | 3.51 (839) |
| 20‡ | 21 | M | 4 | 8.93 (2137) | 9.48 (2269) | 2.55 (610) | 3.10 (742) |
| 21 | 66 | M | 4 | 10.77 (2577) | 10.23 (2448) | 4.01 (959) | 3.47 (830) |
| 22 | 33 | F | 4 | 9.33 (2233) | 9.90 (2367) | 2.93 (701) | 3.49 (836) |

* 20.75-h period.
† 19-h period.
‡ 16-h (three exercise periods).

data from the calorimeter is shown in **Figure 3**. The regression equation

$$y = 0.92X + 1.0 \text{ MJ} \qquad (10)$$

is close to the line of identity. SEE was 0.91 MJ (218 kcal) and $r$ was 0.87. With the calorimeter as the standard, the maximum deviations of the values of TDEE from the heart-rate method for the 22 subjects varied between +20% and −15%. **Figure 4** presents a similar regression analysis for EAC. Again, the regression equation is similar to the line of identity

$$y = 0.87X + 0.52 \text{ MJ} \qquad (11)$$

with $r = 0.87$ and SEE = 0.91 MJ (218 kcal).

With six exercise periods and 22 subjects there would be 132 possible periods of exercise in these experiments. Because of the protocol assignments, (Figure 2) there were 62 nonexercise periods and 65 periods of actual exercise of varying intensity on the bicycle ergometer (Fig 2). The five missing periods were due to the accidents of malfunction of the recorder and electrode detachment mentioned earlier. A plot of the 127 average 30-min EE periods calculated from the heart-rate method and measured in the calorimeter is presented in **Figure 5**. There are 61 points in the lower left square marked off by 10 × 10 kJ/min that were measured during nonexercise periods. Although most of the subjects were seated quietly

during most of these periods, some moving around may have occurred and so they cannot all be accurately described as at rest. One nonexercise measurement shows an abnormally high value obtained from the heart-rate estimate (Fig 5).

Also in Figure 5 there are seven exercise values that showed increased EE by calorimeter measurements but were not detected by the heart-rate method. Three of these occurred during cycling at a work load of 1470 N·m/min (25 W), three at 2940 N·m/min (50 W), and one at 4410 N·m/min (75 W). These seven undetected measurements occurred in five subjects. The remaining 58 points during exercise were measured as shown. The overall regression analysis was very close to the line of identity and despite the eight points that did not show good agreement, $r$ was 0.94 and the SEE was 3.40 kJ/min (0.81 kcal/min). A paired sample analysis of all 127 comparisons did not show a statistically significant difference (Fig 5).

An individual plot of the 30-min averages of EE from 2000 to 1800 the next day for one subject is presented in **Figure 6**; in this female subject the heart-rate method showed a good ability to follow the exercise periods but overestimated TDEE by 0.6 MJ (144 kcal).

EE during sleep was monitored continuously by the calorimeter. It was possible, therefore, to estimate the use of BMR by the heart-rate method for the same period as
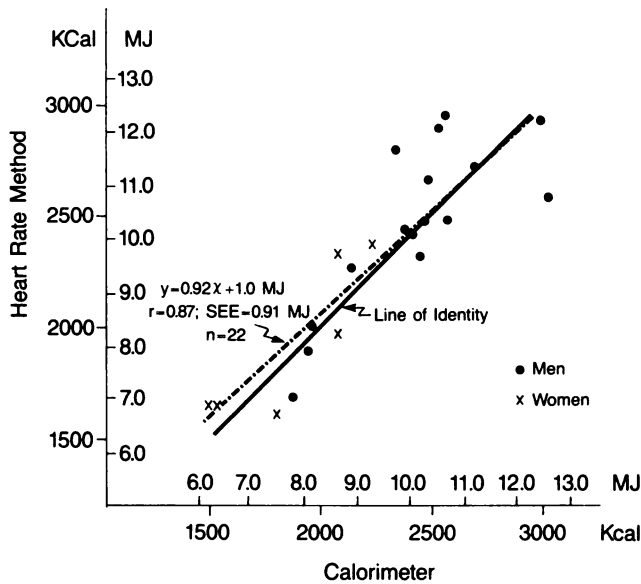
FIG 3. Least-squares regression analysis of total daily energy expenditure measured by the heart-rate method on that measured in the calorimeter.



FIG 5. Regression analysis of energy expenditure obtained by the heart-rate method during all possible periods of exercise or rest of the 22 subjects during 22 h in the calorimeter.

a source of error. For the 22 subjects, mean and SD values for EE during sleep by BMR were $2.6 \pm 0.3$ MJ ($622 \pm 72$ kcal) and by the calorimeter were $2.7 \pm 0.3$ MJ ($646 \pm 72$ kcal). The difference was not statistically significant.

Because the measurement of BMR for use in calculating EE during sleep may be difficult under some field conditions, we have used the prediction equations of Schofield (22) to estimate the BMR of our subjects from sex, age, and body weight. BMR measured by the calorimeter in the 22 subjects was $4.72 \pm 0.58$ kJ/min ($1.13$

$\pm 0.14$ kcal/min) and that estimated by the Schofield (22) equations $4.72 \pm 0.54$ kJ/min ($1.13 \pm 0.13$ kcal/min). Consequently, insofar as the Schofield equations apply to a group of subjects, it may be possible under difficult field conditions to estimate rather than measure BMR and to use the heart-rate recording technique only during the awake portion of the day.

## Discussion

The early literature on attempts to use heart-rate measurements as a means of estimating metabolic rate date back to the work of Benedict in 1907 and was reviewed briefly by Booyens and Hervey (23). These authors early recognized the two phases of the relationship between $\dot{V}O_2$ and fH in individual subjects and the difficulty of estimating metabolic rate from fH at low levels of activ-
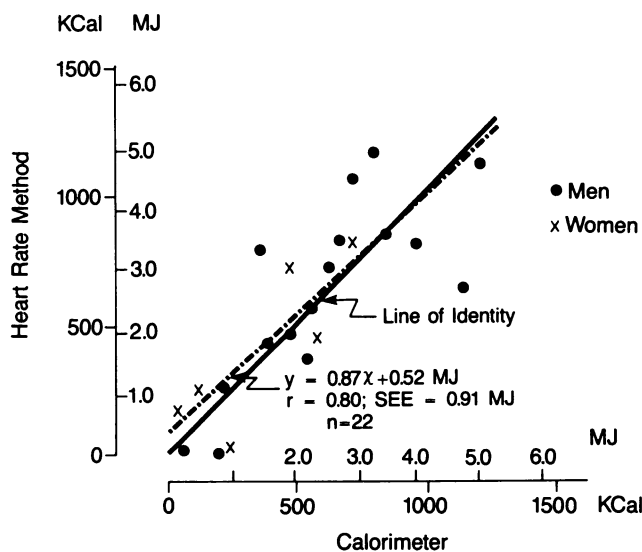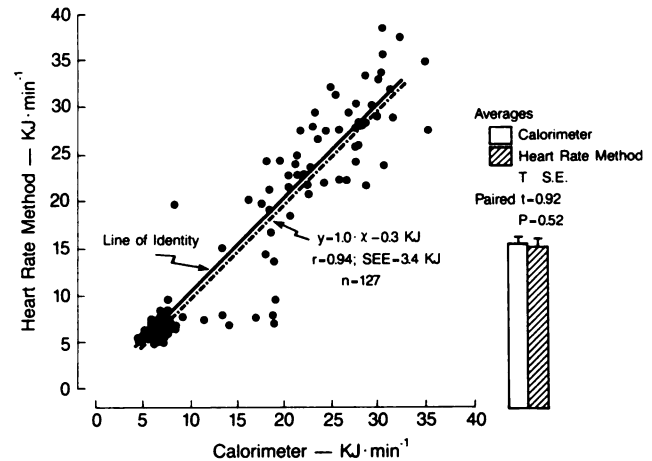


FIG 4. Least squares regression analysis of energy expenditure in activity (above maintenance) measured by the heart rate method on that measured in the calorimeter.
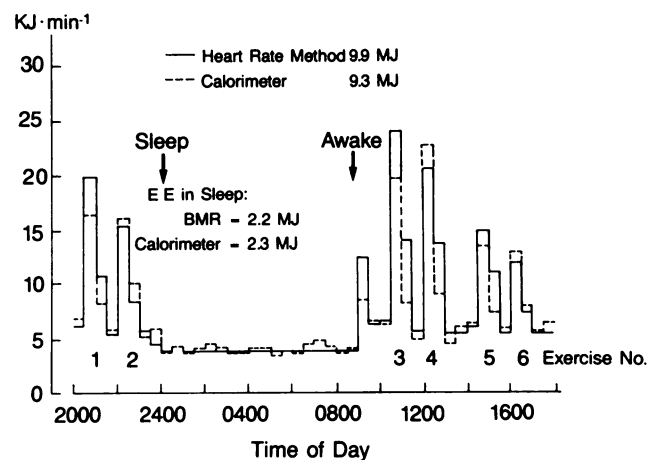


FIG 6. Thirty-minute averages of energy expenditure during 22 h in a subject performing six bouts of exercise (protocol IV). (1 kJ = 0.239 kcal.)

ity. Despite some reports of the satisfactory use of average heart rates accumulated over 24 h in the estimation of daily energy expenditure (24, 25), there has been general dissatisfaction with this approach (26, 27). This is probably because in most adults the average fH over 24 h does not rise very much over values found in resting conditions where the $VO_2$-fH relationship is least precise. However, in children the heart-rate accumulation method used only during the awake, active portion of the day gives average fH values that fall on the steeper part of the individual calibration curve; this results in more acceptable values for TDEE (8, 9, 28).

With the development of small, light devices for minute-to-minute heart-rate recording and computer storage and the ability to examine each fH rapidly by computer techniques, it becomes possible to separate a given fH into the high or low ranges of fH on the calibration curves. This allows for estimation of EE in the low range by use of the average RMR obtained over a range of low-intensity activities or to calculate the EE with the regression equation obtained in higher-intensity activities during the calibration procedure. The success of this approach will be dependent to some extent on the ability to determine fH at the point of flexion of the calibration curves (Fig 1). Because of an overlap in the higher fHs at rest and the lower fHs in exercise, it has been difficult to determine EE from fH in the range 80–120 beats/min (29). In the present experiments the FHFLEX was determined empirically as that measured by calculating the average of the highest fH at rest and the lowest during bicycle exercise plus 10. As employed in this analysis, the results were quite good for group values (Table 2). The data for individual subjects shows a wider variability (Table 3), of course, than for groups but are acceptable measures of TDEE and EAC. These will be greatly improved by repeat measures in the same individual under similar conditions of activity.

The value for RMR obtained during the calibration procedure was compared with that measured by the calorimeter. The latter was calculated from the calorimeter data by excluding all measurements made during sleep, exercise, for the 30-min periods immediately after exercise and for the 30 min before sleep and after awakening in the morning. The values were 6.35 ± 0.83 kJ/min (1.52 ± 0.20 kcal/min) and 6.19 ± 0.71 kJ/min (1.48 ± 0.17 kcal/min) for the calibration procedure and calorimeter, respectively. The difference was not statistically significant ($p = 0.42$). Consequently, the value for RMR obtained during the calibration procedure was comparable with that measured in the calorimeter during most of the awake, inactive portion of the day and did not contribute significantly to differences in the heart-rate method compared with the calorimeter method.

It was suggested (15) that one of the inaccuracies of the minute-by-minute heart-rate method might be due to a slower return of fH to resting levels than the return of EE after bouts of activity. This phenomenon was observed in many of the exercise periods measured in the calorimeter. Because there is also a tendency for a slow return to resting levels in the calorimeter data after exercise, the present experiments provide an opportunity to determine the magnitude of the difference between the two methods. The EE for the 30-min period after exercise was obtained from the calorimeter data and compared with that estimated from fH during the same period for the 65 bouts of exercise. The average values for all periods were 9.56 ± 1.52 kJ/min (2.29 ± 0.36 kcal/min) and 12.47 ± 4.33 kJ/min (2.98 ± 1.04 kcal/min) for the calorimeter and heart-rate methods, respectively. The difference was statistically significant ($p < 0.001$). Both values were significantly correlated with the intensity of the exercise (W): $r = 0.63$ and $p < 0.001$ for the heart-rate method and $r = 0.42$ and $p = 0.002$ for the calorimeter method.

The ability of the heart-rate method to follow the exercise periods of the subjects (Figs 5 and 6) is no doubt at least partially related to the exercise in the calorimeter being the same as that used in the calibration procedure. More studies are needed to compare the two methods using different types of exercise in the calorimeter. Also, comparisons between the heart-rate method and the doubly labeled water technique in free-ranging subjects are needed. Although the heart-rate method will probably never be as accurate as the use of doubly labeled water in measuring individual EE, it can give a close estimate of EE even in small groups (Table 2) and offers an inexpensive way of obtaining reasonably accurate data in free-ranging subjects. Furthermore, the heart-rate method can give information on the pattern of daily activity (Fig 6) not provided by the doubly labeled water technique.

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