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The use of heart rate monitoring in the estimation of energy expenditure: a validation study using indirect whole-body calorimetry

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1. A modified heart rate (HR) method for predicting total energy expenditure (TEE) was cross-validated against whole-body calorimetry (CAL). Minute-by-minute HR was converted to energy expenditure (EE) using individual calibration curves when HR exceeded a pre-determined 'FLEX' value designed to discriminate periods of activity. ('FLEX' HR was defined as the mean of the highest HR during rest and the lowest HR during the lightest imposed exercise.) Sedentary EE (below FLEX) was calculated as the mean EE during lying down, sitting and standing at rest. Sleeping EE was calculated as basal metabolic rate (BMR) predicted from standard equations.

2. Calibration curves of oxygen consumption *v*. HR for different postures at rest and during exercise were obtained for twenty healthy subjects (eleven male, nine female); mean *r* 0·941 (SD 0·04). The mean FLEX HR for men and women were 86 (SD 10) and 96 (SD 6) beats/min respectively.

3. Simultaneous measurements of HR and EE were made during 21 h continuous CAL, which included 4 × 30 min imposed exercise (cycling, rowing, stepping, jogging). HR exceeded FLEX for a mean of 98 (SD 41) min. Mean TEE by CAL (TEE . CAL) was 8063 (SD 1445) kJ.

4. The HR method yielded a mean non-significant underestimate in TEE (TEE . HR) of 1·2 (SD 6·2) % (range $-11{\cdot}4$ to $+10{\cdot}6$ %). Regression of TEE . HR (Y) *v*. TEE . CAL (X) yielded $Y = 0{\cdot}868\ X + 927$ kJ, *r* 0·943, SE of the estimate 458 kJ, *n* 20.

5. The satisfactory predictive power and low cost of the method makes it suitable for many field and epidemiological applications.

Human energy expenditure (EE) can be accurately measured using whole-body calorimeters (Dauncey & James, 1979; Prentice *et al.* 1985) or the doubly-labelled water method (Prentice *et al.* 1984). However, the former restricts subjects within an artificial environment, and the latter is expensive and requires considerable expertise. A third possible method requires the use of activity diaries (Acheson *et al.* 1980; Geissler *et al.* 1986) in which detailed time-and-motion records are converted to EE using subject-specific or tabulated values for the energy cost of each activity. This method has been applied to relatively large samples (Durnin & Passmore, 1967), but is very labour intensive, intrusive and of limited precision.

In an attempt to develop a simpler technique which could be applied in large epidemiological studies, several investigators have explored the possibility of predicting EE from heart rate (HR) (Bradfield, 1971; Bradfield *et al.* 1971; Payne *et al.* 1971; Warnold & Lenner, 1977). However, earlier cross-validation studies against whole-body calorimetry (CAL) demonstrated a poor level of precision (Dauncey & James, 1979; Avons *et al.* 1988). This was probably attributable to the use of a mean HR value over long periods of low activity, including sleep, and to the method of calibration used.

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With recent developments in micro-chip technology there are now a number of ambulatory HR monitors available which record minute-by-minute HR throughout the day, and from which information retrieval is extremely easy. These allow a different EE to be assigned to each minute's activity, and should theoretically yield a substantial improvement in the predictive power of the method. This has been confirmed in an earlier cross-validation study from this laboratory employing prototype HR monitors (Spurr *et al.* 1988). A potential criticism of this study was that it favoured a good result by using the same type of exercise during calibration and test periods. In the present study minute-by-minute monitoring has been revalidated using a commercially available monitor under more rigorous conditions by imposing a variety of different exercise types during calibration and in a 21 h test period of CAL.

SUBJECTS AND METHODS

Twenty volunteers (eleven males, nine females) were recruited by advertisement. All were healthy non-smokers and had not taken any medication during the month before study. The mean age was 25 (range 17–36) years, mean weight 67·0 (range 53–78) kg, and mean height 1·72 (range 1·57–1·84) m. The study was approved by the Dunn Nutrition Unit Ethical Committee and written informed consent obtained from the subjects.

The Sports Tester PE3000 HR monitor (Polar Electro, Finland) consists of a comfortable chest belt which transmits HR values to a 'wrist-watch' receiver. Skin contact was made via conductive rubber electrodes behind the belt which require no adhesive or electrode gel. HR was continually assessed from the electrocardiograph (ECG) signal after computerized noise filtering and could be stored as 5, 15 or 60 s averages. In the 60 s mode used in the present study the storage capacity is approximately 17·0 h. Data were retrieved via an interface unit and a BBC microcomputer for which additional programs were written to convert HR to EE.

Each subject was individually calibrated using standard techniques to obtain the relation between HR and oxygen consumption (V_{O_2}). After arriving at the laboratory and resting for 20–30 min, simultaneous measurements were made of HR (PE3000) and V_{O_2} whilst lying supine, sitting, standing quietly with minimal movement and whilst performing the following exercises: cycle ergometer (Model 868; Monark, Sweden) at 50 rev./min and work loads of 25, 50, 75 and 100 watts; stepping at twenty steps/min on and off a 225 mm block; jogging on the spot at 138 steps/min. Each exercise measurement consisted of a 3 min equilibration period followed by a 3 min measurement. Subjects rested for 5 min between exercises. Respiratory volume was measured using a mouthpiece, a nose clip and ventilation monitor. O_2 uptake measurements were made with a paramagnetic O_2 analyser (Model OA 137; Taylor Servomex Ltd, Crowborough), and carbon dioxide measurements with an infra-red analyser (model 801; P. K. Morgan Ltd, Chatham). EE during calibrations was calculated using the simplified Weir (1949) formula which assigns 20·5 kJ (4·9 kcal)/l O_2 consumed.

The multiple exercise levels were used to check the linearity of each subject's calibration curve. However, in field use it would be more convenient to use a smaller number of calibration points, especially in large sample studies. The analysis presented here was, therefore, performed by deriving the calibration curves from linear regression of the lying, sitting, standing, 50 watts cycling and stepping measurements.

EE was calculated from HR using a modification of the method of Spurr *et al.* (1988). This requires the definition of a 'FLEX' HR for each subject, above which there is a strong relation between HR and V_{O_2}, and below which the two variables are rather poorly correlated (due largely to the influence of posture on stroke volume) (Morehouse & Miller, 1967). In the present study 'FLEX' HR was defined as the mean of the highest HR during the standing measurements and the lowest HR during stepping measurements.

Total EE (TEE) during the CAL periods was predicted from HR as:

$$\text{TEE} = \sum \text{sleep EE} + \sum \text{sedentary EE} + \sum \text{activity (exercise) EE}.$$

Sleep EE was assumed to equal basal metabolic rate (BMR), as predicted from standard equations (Schofield *et al.* 1985). This conversion is consistent with the proposed field use of the method. Sedentary EE was defined as all non-sleeping time when HR was below FLEX, and was calculated as the mean EE for the lying down, sitting and standing periods during calibration. On average sedentary EE was 1·38 (SD 0·06) × Schofield (Schofield *et al.* 1985) BMR. Activity EE was calculated by applying each individual's calibration line to HR in excess of FLEX. The calculation was performed separately on each minute's values.

Within 7 d of calibration, each subject spent 21·5 h in one of the Dunn Clinical Nutrition Centre's whole-body calorimeters. Simultaneous measurements of HR and V_{O_2} were made throughout. Calorimeter V_{O_2} values were calculated at 200 s intervals using the fast-response equations described by Brown *et al.* (1984), which result in a negligible lag time. The calorimeter protocol was as follows: 19.00 hours meal, 19.30 hours HR monitor on, 20.00 hours enter calorimeter, data collection starts, 21.00 hours cycle at 50 watts for 30 min (25 watts for some subjects), 22.30 hours prepare for bed (unfold bed, re-arrange furniture, wash, undress), 23.00 hours lights out, 08.00 hours woken for 60 min supine BMR measurement, 09.00 hours rise (fold bed, re-arrange furniture, wash, dress), 09.30 hours change monitors, breakfast, 10.30 hours row/cycle at 50 watts for 30 min, 12.30 hours stepping for 30 min, 13.30 hours lunch, 16.30 hours jogging on the spot for 30 min, 17.30 hours come out of calorimeter. Subjects stood up for 5 min before and 10 min after each exercise period. Exercise rates were: cycling 50 rev/min, rowing 20 strokes/min, stepping 20/min, jogging 138 steps/min. Some subjects performed a second period of cycling instead of rowing, since rowing required more skill.

Statistical analysis was performed using paired *t* tests and linear regression.

RESULTS

A calibration test was performed in which the HR meter PE3000 was compared with a multi-lead reference ECG at HR up to 164 beats/min. Linear regression produced *r* 0·999 with a slope of 0·96 and an intercept of 3·5 beats. The results confirm the manufacturer's claims for the high performance of the PE3000.

All studies which have attempted to predict EE from HR agree on the need to obtain individual calibration curves for each subject (Booyens & Hervey, 1960; Taylor *et al.* 1984). Goldsmith *et al.* (1966) reported that a large variation existed in these curves. This was further emphasized in the current study by the wide range in both the slopes and the intercepts from individual calibration lines. The mean linear correlation coefficient from all calibrations was 0·941 (SD 0·04). There was a wide variation between individuals in the values selected for FLEX HR. The authors will address this point in a separate paper. At this point it is necessary to point out that inter-individual differences may be attributed to differences in resting HR and condition of fitness (Pollack *et al.* 1980).

Table 1 shows the subjects' details and compares TEE derived from the HR (TEE . HR) method with the CAL (TEE . CAL) reference values. The observed mean daily HR during the 21 h of calorimetry was 72·4 (SD 7·9) beats/min (*n* 20). For seven subjects the period of comparison was less than the intended 21 h due to interruptions in the HR record. All missing values occurred during sleep periods when EE is assumed to equal BMR in the

Table 1. *Comparative values of the mean total energy expenditure (TEE) measured by the heart rate (HR; TEE. HR) and whole-body calorimetry (CAL; TEE. CAL) methods* for healthy volunteers (n 20)*

Subject no.	Sex	Age (years)	Wt (kg)	Mean HR (beats/min)	FLEX HR (beats/min)	TEE. HR (kJ)	TEE. CAL (kJ)	Time (h)	Error (%)
01	♀	28	57·8	76·3	106	7360	7383	21	−0·3
02	♂	23	70·7	70·0	89	8781	8856	21	−0·8
03	♀	26	62·3	77·5	94	6957	6988	21	−0·4
04	♂	26	72·1	70·1	90	9966	9330	21	+6·8
05	♀	21	70·3	78·4	98	8713	9610	21	−9·4
06	♀	27	63·6	79·6	90	7829	8219	21	−4·8
07	♂	17	68·1	58·0	99	5988	5676	13	+5·5
08	♂	27	65·9	62·4	92	8332	9401	21	−11·4
09	♀	32	60·3	58·7	96	4812	4351	13·5	+10·6
10	♂	22	78·1	68·4	99	9507	9798	21	−3·0
11	♂	36	71·2	69·2	89	7697	8253	21	−6·8
12	♂	26	68·7	70·7	86	7249	7623	14	−4·9
13	♂	24	65·5	76·3	80	7573	7328	12	+3·3
14	♂	17	58·4	68·6	89	9749	10076	21	−3·3
15	♀	20	72·7	83·9	103	8446	8504	21	−0·7
16	♀	23	64·5	75·1	89	8333	8603	21	−3·2
17	♀	28	74·2	88·0	93	6793	6799	16·5	−0·1
18	♂	35	68·9	67·3	93	8718	8010	16	+8·8
19	♂	29	74·6	68·6	86	9329	9269	16	+0·6
20	♀	22	53·5	80·9	98	6373	7185	21	−11·4
Mean		24·5	67·1	72·4	92·9	7925	8063	18·7	−1·2
SD		7·3	6·4	7·9	6·3	1329	1445	—	6·2
SE						297	323		
CV(%)						16·7	17·9		

FLEX HR, mean highest HR during the standing measurements and the lowest HR during stepping measurements; CV, coefficient of variation.

* For details of procedures, see pp. 176–177.

method proposed in the present paper. The loss of values, therefore, made little difference to the interpretation of the results, and in field use it will not be necessary to wear the monitor during sleep.

On average the HR method underestimated TEE by only −1·2 (SD 6·2; range −11·4 to +10·6) %. The difference between the two methods was not significant (paired *t* −1·28). For additional information, analysis of the sexes separately showed a slight underestimation by the HR method in both groups, although this was not significant: females −2·2 (SD 6·3) % (paired *t* −1·59, not significant (NS)); males −0·5 (SD 6·2) % (paired *t* −0·42, NS).

Fig. 1 illustrates the correlation between the two methods. Linear regression of TEE. HR (Y) on TEE. CAL (X) yielded $Y = 0{\cdot}868\,X + 927$ kJ (r 0·943, n 20). The slope and the intercept were not significantly different from unity and zero respectively. The standard error of the estimate was 458 kJ.

A comparison of EE measured by the two methods during the night (20.00 hours–09.00 hours) is shown in Table 2 for the fifteen subjects for whom complete information was available. The HR method yielded a significant underestimate of EE: −6·2 (SD 5·78) % (paired *t* −3·72, $P < 0{\cdot}01$). Night-time EE was derived largely from the Schofield (Schofield *et al.* 1985) estimate of BMR (510/780 min), but also included 60 min of activity (30 min cycling and 30 min undressing and washing). The remaining 210 min were calculated

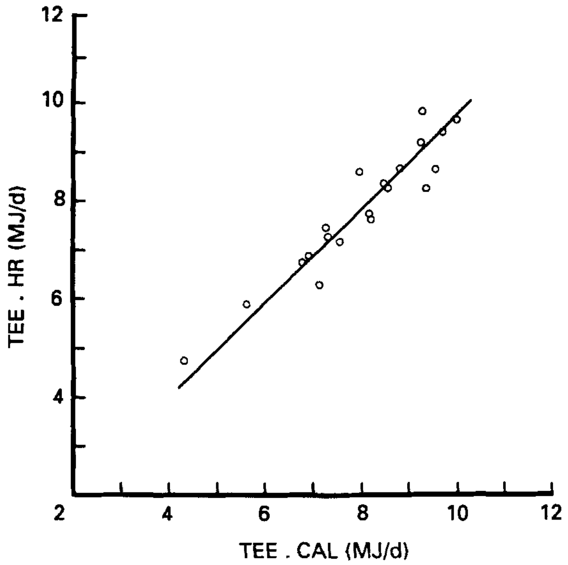

Fig. 1. Correlation between total energy expenditure (TEE) derived from the heart rate (HR; TEE . HR) and whole-body calorimetry (CAL; TEE . CAL) methods (*n* 20). *r* 0·943, slope 0·868, intercept 927 kJ, SE of estimate 458 kJ. For details of methods, see pp. 176–177.

Table 2. *Comparison of night-time energy expenditure (NEE) (20.00–09.00 hours) measured by the heart rate (HR; NEE . HR) and whole-body calorimetry (CAL; NEE . CAL) methods* for healthy volunteers (n 15)*

Subject no.	Mean HR (beats/min)	NEE . HR (kJ)	NEE . CAL (kJ)	Error (%)
01	66·4	4722	4873	−3·2
02	61·7	4480	4531	−1·2
03	77·0	4512	4556	−1·0
04	61·6	4927	4933	−0·2
05	66·6	4436	5109	−13·2
06	63·5	3956	4260	−7·2
08	53·2	4186	4553	−8·1
10†	58·8	4892	4643	+5·4
11	64·7	4774	5154	−7·3
12	67·2	2512	2658	−5·5
13	70·9	2148	2286	−6·1
14	62·1	5094	5607	−9·2
15	75·7	5046	5329	−5·4
16	66·6	4001	4641	−13·8
20	78·9	4570	5497	−16·9
Mean	66·3	4284	4644	−6·2
SD	7·0	867	981	5·8
SE	1·8	224	253	
CV(%)	10·5	20·2	21·1	

CV, coefficient of variation.

* For details of procedures, see pp. 176–177.

† No exercise done.

Table 3. *Comparison of daytime (09.00–17.00 hours) energy expenditure (DEE) measured by heart rate (HR; DEE . HR) and whole-body calorimetry (CAL; DEE . CAL) methods* for healthy volunteers (n 20)*

Subject no.	Mean HR (beats/min)	DEE . HR (kJ)	DEE . CAL (kJ)	Error (%)
01	86·3	2638	2510	+5·0
02	78·4	4301	4325	−0·6
03	78·1	2445	2431	+0·6
04	78·6	5039	4396	+14·6
05	90·3	4277	4500	−5·0
06	95·8	3873	3959	−2·2
07	58·1	5988	5676	+5·5
08	71·8	4146	4848	−15·0
09	58·7	4012	4351	+10·6
10	78·1	4614	5155	−10·5
11	73·8	2922	3099	−5·7
12	74·2	4737	4965	−4·6
13	81·7	5424	5042	+7·5
14	75·3	4655	4468	+4·0
15	92·0	3399	3174	+7·1
16	83·5	4332	3962	+9·3
17	88·0	6793	6799	−0·1
18	67·3	8718	8010	+8·8
19	68·6	9329	9269	+0·6
20	83·0	1802	1688	+6·7
Mean	78·1	4712	4631	+1·8
SD	10·1	1896	1820	7·5
SE	2·3	424	407	
CV(%)	13·0	40·2	39·3	

CV, coefficient of variation.
* For details of procedures, see pp. 176–177.

as sedentary EE. In these subjects the Schofield (Schofield *et al.* 1985) predictions underestimated measured BMR by −4·3 (SD 7·7)% (paired t 2·10, $P < 0{\cdot}06$). This, therefore, accounted for much of the error in the HR method.

Table 3 shows a similar comparison of daytime EE (DEE) for all twenty subjects. During this period the HR method involves just two components: predictions from individual calibrations above FLEX HR and use of sedentary EE below FLEX. The two methods, HR (DEE . HR) and CAL (DEE . CAL), were highly correlated with a slope close to unity: DEE . HR = 1·027 DEE . CAL −85 kJ (r 0·983, $P < 0{\cdot}001$). On average the HR method produced a slight overestimate of DEE: +1·8 (SD 7·5)% (paired t 0·52, NS).

The ability of the HR method to predict the energy cost of the four imposed exercise periods, each of 30 min, is summarized in Table 4. The HR estimate was significantly lower than the CAL estimate: −11·6 (SD 16·5)% (paired t −2·75, $P < 0{\cdot}02$). Individual errors ranged from −39·5 to +18·6%. When the HR method underestimated the cost of exercise this was usually because the exercise failed to raise HR above the predetermined FLEX. In field use the importance of this error will depend on the relative proportion of time spent being active and inactive.

Fig. 2 illustrates representative traces of EE measured by CAL and predicted values from HR or from sedentary EE or BMR. Results were calculated over 30 min intervals. The HR trace illustrates the three-component method of calculation used. The use of an estimated sedentary EE for HR below FLEX (other than during sleep) clearly fails to follow the fine

Table 4. *Comparison of energy expenditure during 2 h of imposed exercise*. Exercise energy expenditure (EEE) measured by the heart rate (HR; EEE.HR) and whole-body calorimetry (CAL; EEE.CAL) methods† for healthy volunteers (n 18)*

Subject no.	EEE.HR (kJ)	EEE.CAL (kJ)	Error (%)
01	2035	1987	+2·4
02	1923	2320	−17·1
03‡	986	1376	−28·3
04	3127	2637	+18·6
05	2131	2363	−9·8
06	2104	2363	−11·0
07	—	—	—
08	2159	2512	−14·0
09	—	—	—
10	2025	2755	−26·5
11‡	1016	1200	−15·3
12	1982	2782	−28·7
13	2713	2768	−2·0
14	2738	2554	+7·2
15	2243	2037	+10·1
16	2391	2283	+4·7
17	819	854	−4·2
18	1432	2197	−34·8
19	1819	2315	−21·4
20§	948	1566	−39·5
Mean	1922	2159	−11·6
SD	656	563	16·5
SE	154	132	
CV(%)	34·0	26·0	

CV, coefficient of variation.

* 30 min each of cycling, stepping, rowing and jogging; subject no. 17 only completed 1 h of exercise.

† For details, see pp. 176–177.

‡ All four sessions were 25 watts cycling.

§ Only 90 min of activity.

detail of changes in EE, but nonetheless provides a very good match on average. As indicated in Table 4 the HR method sometimes failed to discriminate periods of exercise. Examples of this can be seen in both traces in Fig. 2. On other occasions the HR method detected the exercise, but provided a relatively poor estimate of its true cost.

Fig. 3 combines the values from the present study with that of a previous study performed at the Dunn Nutritional Laboratory in Cambridge (Spurr *et al.* 1988) in which both the calibration and test exercises consisted entirely of cycling. Inclusion of these values considerably extends the range over which the two methods can be compared. The mean HR error overestimated TEE.CAL by only 0·6 (SD 8·0)%. Regression analysis yielded TEE.HR = 0·962 TEE.CAL + 389 kJ (*r* 0·912, *n* 42, SE of the estimate 754 kJ).

The mean sedentary EE measured during calibrations was 1·38 (SD 0·06) × Schofield (Schofield *et al.* 1985) BMR or 1·35 (SD 0·07) × measured BMR. Average TEE measured (*n* 20) during the calorimetry periods was 1·64 (SD 0·15) × BMR.

DISCUSSION

Most previous attempts to predict EE from HR have been based on accumulated or averaged HR over the entire period of time under investigation, or over extended

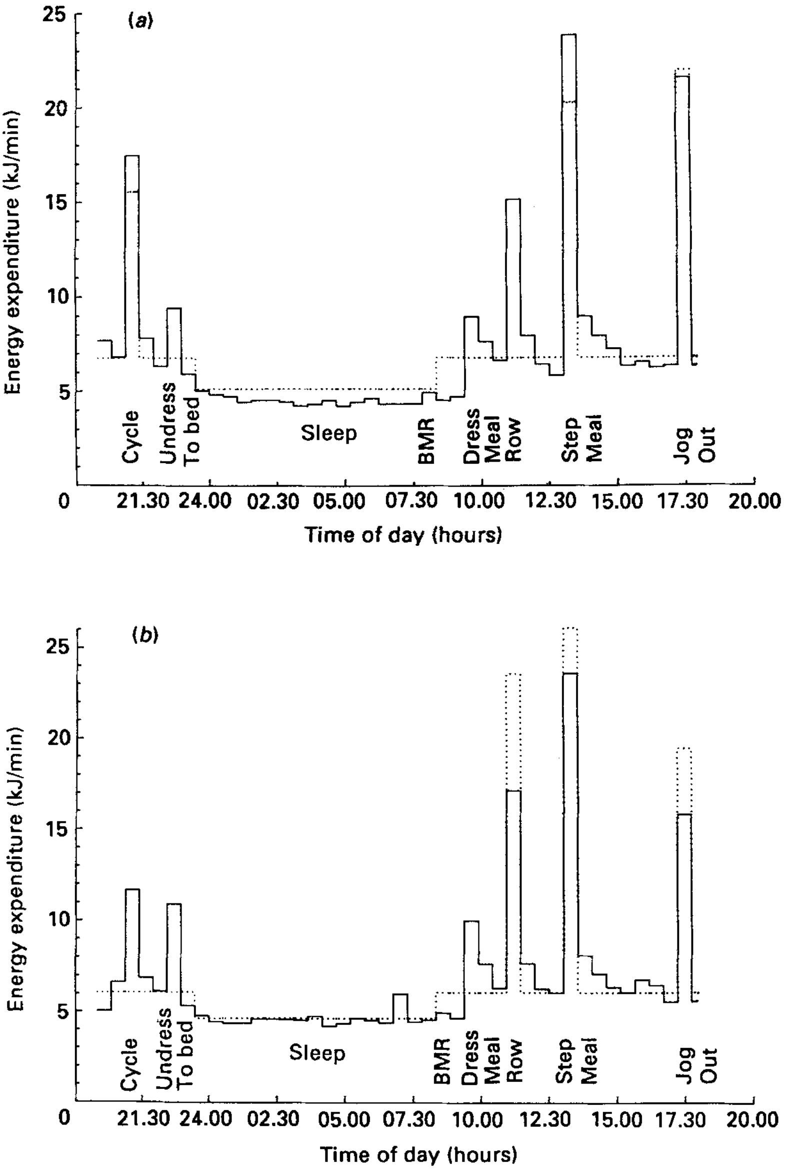

Fig. 2. Examples of calorimeter (———) and heart rate (.....) traces from two subjects. (*a*) Subject no. 02 (age 23 years, weight 70·7 kg, FLEX 89); (*b*) subject no. 15 (age 20 years, weight 72·7 kg, FLEX 103). FLEX, mean of the highest heart rate during the standing measurements and the lowest heart rate during stepping measurements; BMR, basal metabolic rate. For details of procedures, see pp. 176–177.

subperiods of the total (Payne *et al.* 1971; Acheson *et al.* 1980; Christensen *et al.* 1983; Geissler *et al.* 1986; Avons *et al.* 1988). The mean HR is usually converted to EE from individual regression lines derived by calibrating each subject with a series of submaximal work loads. The main problem with this approach is that it fails to allow for the fact that, although HR and EE are closely correlated during exercise, there is often no discernible relation during periods of light activity or rest. Under most circumstances mean HR over

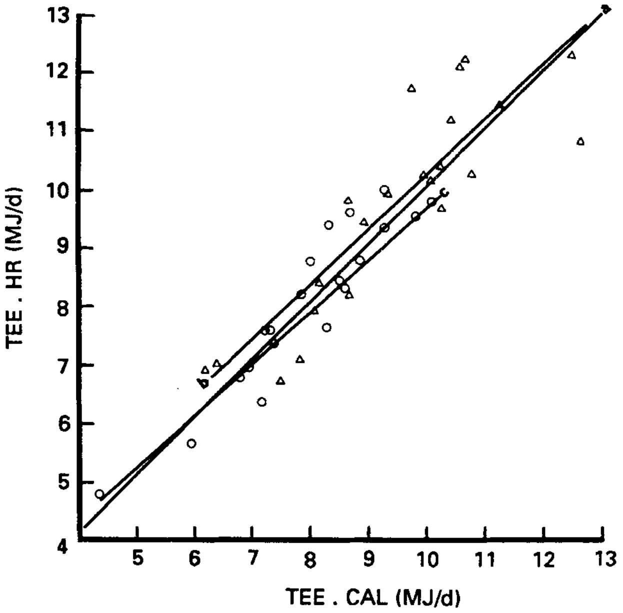

Fig. 3. Total energy expenditure (TEE) values from the present study (○) and the study of Spurr *et al.* (1988) (△) employing a different methodology. (*a*) Regression line for both studies combined (*n* 42); (*b*) regression line in the Spurr *et al.* (1988) study (*n* 22); (*c*) regression line in the present study (*n* 20). TEE . HR, TEE derived from the heart rate method; TEE . CAL, TEE derived from the whole-body calorimetry method. For details of methods, see pp. 176–177.

an entire day are quite close to resting HR. For instance Dauncey & James (1979) reported mean 24 h HR of 68 and 71 beats/min in eight subjects on light and moderate activity protocols. As pointed out by these authors, the calibration curves are, therefore, being used to predict EE in precisely the region over which they are known to be least accurate, and any potential errors are multiplied up over the entire day. As a result of this the method yielded poor results when cross validated against continuous CAL (Dauncey & James, 1979; Avons *et al.* 1988).

Recently Spurr *et al.* (1988) proposed a new approach, taking advantage of technological improvements which make it possible to obtain accurate minute-by-minute records of HR throughout the day. Using this approach the HR measurements are only used to predict EE during minutes of activity when the relation is known to be fairly secure. During periods of inactivity the method acknowledges that HR cannot be used to predict EE and substitutes an individually determined value for sedentary EE. During sleep the method substitutes BMR, which may be measured or predicted from standard equations. Discrimination of exercise periods is achieved by pre-determining a cut-off HR (FLEX) for each subject above which the calibration curve will be applied.

The present study aimed to validate the modified HR technique under more rigorous conditions by employing four different exercise types. The results showed a mean discrepancy of only −1·2 (SD 6·2)% (*n* 20) when compared with indirect calorimetry. This shows a good agreement with results published by Dauncey & James (1979), using the CAL method, where the mean error was −3 (SD 6·7)% over a 24 h period. Pooling the values from the present study and that of Spurr *et al.* (1988) provided a range of EE from 4·8 to 12·5 MJ, and a correlation coefficient of *r* 0·912 with SE of the estimate 754 kJ. We, therefore, conclude that the FLEX HR method provides accurate group estimates of TEE, and that the precision of individual estimates is better than ± 10 %.

The ultimate accuracy of the method in field applications will depend on the activity profiles of the subjects being studied. In very inactive subjects the HR measurements will contribute little to the final estimate of expenditure, since they will rarely exceed the FLEX threshold. In such circumstances the resultant combined use of BMR and sedentary EE values, plus a minimal increment for activity, will probably give a very realistic estimate of expenditure, and although the HR measurements will have had little impact on the calculation, they will have been important in demonstrating that the subject was very inactive.

At the other end of the range we have field information from very active subjects who spend more than 80 % of the daytime with HR above FLEX. Under these circumstances the accuracy of the final result will be heavily dependent on the calibration line, and the appropriateness of the pre-determined FLEX. In the present study the HR method produced a significant underestimate of the energy cost of the imposed exercises, and individual errors ranged from −39·5 to +18·6 % over the 2 h period. The underestimate was largely caused by the fact that some of the exercises failed to raise HR above FLEX, suggesting that the choice of FLEX was too high or that the work load performed was not heavy enough to show any significant rise in HR. This could become a major problem in subjects who spend many hours involved in activities which are above sedentary EE but below the FLEX threshold. In such circumstances the HR method could yield a very substantial underestimate of EE, unless great care is taken in identifying a suitably accurate FLEX value. This problem will not arise in people performing episodic activities, since HR will usually be clearly above or below FLEX. In very active subjects who are involved in a particular task for many hours (eg. subsistence farming: hoeing, planting, weeding or harvesting), optimal results will be achieved by establishing their individual calibration lines using imposed activities which simulate the posture and movements of the real tasks.

In the first study we tested the following algorithms for defining FLEX: (a) visual inspection of the calibration curve; (b) the mean of the highest HR during rest and the lowest during the lightest imposed exercise; (c) FLEX as defined in (b) +5, +10, +15 and +20 beats/min. The optimum FLEX was then selected empirically by testing for the best fit and lowest SE of the estimate in the cross-validation study. The estimate based on (b) +10 beats/min emerged as the best option. This yielded a mean FLEX value of 91 (SD 8) beats/min. This value was very similar to that obtained in the current study (93 (SD 6) beats/min) using a simplified definition in which FLEX was set at the mean of the highest HR during standing measurements and the lowest HR during stepping measurements.

The substitution of BMR to represent the energy cost of sleep has recently been shown to be valid. Goldberg *et al.* (1988) analysed CAL values from a large number of subjects in different physiological states and showed that BMR resulted in an average overestimate of about 5 % during the actual hours of sleep, but that this contributed only a 1·6 % error over 24 h. In the present study we used Schofield (Schofield *et al.* 1985) estimates of BMR, since in field use the measurement of true BMR would be difficult to achieve and would add an extra layer of complexity to what is intended to be a simple and robust method. On an individual basis the coefficient of variation for Schofield estimates about measured BMR is about 8 %. This must be accepted as a contributory error in individual TEE estimates, but since it will usually be applied to only one-third of the day its impact is not large.

The choice of an appropriate value for non-sleeping energy expenditure below FLEX (sedentary EE) is particularly critical in inactive subjects. In theory this value should represent the daytime expenditure averaged over all periods of light or minimal activity, in all postures, and should include diet-induced thermogenesis. Clearly it is impossible to make a direct assessment of this without a whole body calorimeter and an estimate must be used. In the present study sedentary EE was defined as the mean EE during the lying down, sitting and standing periods of the calibration. Subjects were calibrated between 2 and 5 h after a meal, and these estimates, therefore, probably include a reasonable estimate of average diet-induced thermogenesis. The mean sedentary EE was 1·38 times Schofield (Schofield *et al.* 1985) BMR or 1·35 times measured BMR. The appropriateness of this value was cross-checked using the CAL values. Subtraction of the energy cost of sleep and of imposed activity and exercise left a residual expenditure corresponding to the desired estimate of minor physical movements plus thermogenesis. This value also averaged 1·38 times BMR, confirming the validity of the sedentary EE value for the group as a whole.

This modified HR FLEX method is not as accurate as the doubly-labelled water technique, but has advantages in terms of cost and ease of use. It may be particularly suitable for large-scale epidemiological studies, such as those investigating the link between activity and coronary heart disease in which the ability to divide large numbers of subjects into quartiles of activity may be more important than absolute accuracy. For such studies the next level of validation must be to quantify the extent of within-subject day-to-day variability in order to determine how many days' measurements are required in order to establish a person's habitual activity pattern. The ability of the HR method to provide information on within- and between-day variability in activity makes it actually preferable to the doubly-labelled water method for certain purposes, irrespective of the cost differential. We, therefore, believe that with prudent application, under appropriate circumstances, the HR method can now be used as a useful adjunct to other methods of estimating EE.

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