Br. J. Nutr. (1979), **42**, 1

Assessment of the heart-rate method for determining energy expenditure in man, using a whole-body calorimeter

BY M. J. DAUNCEY AND W. P. T. JAMES
MRC Dunn Calorimetry Group, ARC Institute of Animal Physiology, Babraham, Cambridge CB2 4AT

(*Received* 24 *July* 1978 – *Accepted* 2 *October* 1978)

1. The heart-rate (HR) method for determining the energy expenditure of free-living subjects has been evaluated using a whole-body calorimeter in which individuals lived continuously for 27 h while carrying out normal daily activities. Eight male volunteers each occupied the calorimeter on at least two occasions when HR and energy expenditure were measured continuously.

2. After each session in the calorimeter a calibration was obtained using standard techniques by determining HR and heat production (HP) over periods of 10–15 min at several levels of activity. Energy expenditure in the calorimeter was then predicted, by each of five methods, from the mean HR in the calorimeter. Additionally, one session in the calorimeter was used to obtain a calibration and was used for predicting the subject's energy expenditure while in the calorimeter on other occasions.

3. Standard methods of prediction using one calibration point at rest and several points during activity were unreliable for predicting the energy expenditure of an individual. The 24 h HR was at the lower end of the calibration scale and there were considerable over-estimates or underestimates of energy expenditure, particularly during the night when the mean ($\pm$SD) difference between the actual and predicted HP was $-66\pm38.6\%$. A linear regression fitted to points at the lower levels of activity improved the prediction of 24 h HP while a logistic plot reduced the error even further. The best estimate of energy expenditure was that obtained from a calibration over 24 h within the calorimeter; the mean ($\pm$SD) difference between the actual and predicted 24 h HP was $+3\pm10.5\%$ for light activity and $-3\pm6.7\%$ for moderate activity. Thus current procedures for calibrating subjects may lead to large errors which could be reduced by using a respiratory chamber.

In order to study the energy metabolism of humans over 24 h periods there is a need to develop a method which does not impose restrictions on the subject or require the prolonged use of unfamiliar apparatus such as a mask. One such method is to use the relation between heart-rate (HR) and energy expenditure and several studies have explored this technique in both man (Bradfield, 1971; Poleman *et al.* 1972) and other species such as sheep (Webster, 1967; Brockway & McEwan, 1969), cattle (Yamamoto *et al.* 1977) and duck (Wooley & Owen, 1977). Studies on man have involved calibrating the subject by measuring both HR and heat production (HP) at several levels of activity over short periods of time (Bradfield, 1971). No information is available about the extent to which the relation determined by these measurements is applicable to the estimation of energy expenditure over 24 h.

Earlier studies on the relation between HR and HP drew attention to a number of technical difficulties. Booyens & Hervey (1960) found that during quiet activities such as lying and sitting the relation between HR and HP showed more variation than during exercise. Payne *et al.* (1971) also commented on the effect on HR of a change in posture between supine and standing positions. Another problem concerns the variations between individuals in the relation between HR and energy expenditure even when each calibration point is determined over a 2 h period (Goldsmith *et al.* 1966). Standard methods of calibration involve measuring HR and HP simultaneously while the subject carries out a number of activities similar to those which may be encountered in a 24 h period. The variety of ways in which the calibration results can be used to estimate 24 h energy expenditure have been investigated by Warnold & Arvidsson Lenner (1977). In contrast with other workers (Booyens & Hervey, 1960; Andrews, 1971; Berg, 1971), Warnold & Arvidsson

0007-1145/79/3203-0210 $01.00

Table 1. *Details of subjects*

Subject no.	Age (years)	Height (m)	Weight (kg)	SA* (m^2)	Difference between actual and desirable weight† (%)
001	37	1·71	65·9	1·77	+4·8
002	26	1·78	68·5	1·85	−0·1
003	47	1·72	56·2	1·67	−13·2
004	30	1·84	99·5	2·23	+36·9
005	62	1·80	87·6	2·07	+24·0
006	23	1·89	60·6	1·84	−21·3
007	30	1·80	63·2	1·81	−10·5
008	37	1·68	56·6	1·64	−7·0
Mean	36·5	1·78	70·0	1·86	+1·7
SD	12·8	0·07	15·6	0·20	19·7

SA, Surface area.
* Calculated from DuBois & DuBois (1916).
† Desirable weight taken as mid-point of medium-frame size from Metropolitan Life Insurance Company (1960).

Lenner (1977) reported that the use of separate regression lines which correspond to different levels of activity was unnecessary.

From the previously mentioned considerations it is apparent that the use of HR for predicting energy expenditure over 24 h is not yet securely based. There is uncertainty about the postures which should be used during the calibration and about the way in which the resulting curves should be used. The present study has evaluated the use of standard calibration procedures to predict the actual energy expenditure of subjects carrying out near-normal activities while living in a whole-body calorimeter for 27 h. A preliminary report of this work has been published (Dauncey & James, 1977).

METHODS

Subjects

Eight male volunteers took part in the study. Their mean ($\pm$SD) height, weight and age were $1·78 \pm 0·07$ m, $70 \pm 15·6$ kg and $36·5 \pm 12·8$ years respectively and anthropometric indices for each subject are given in Table 1. All the subjects were familiar with laboratory surroundings and experimental procedures although none had previously taken part in experiments with a human calorimeter. None of the subjects was known to have any disease, disability or infection. Subject no. 004 was the only smoker but he did not smoke during the experiment.

Experimental procedure

Each subject occupied the calorimeter for 27 h, from 09.30 hours on day 1 to 12.30 hours on day 2. A calibration of HR *v*. HP was then performed in a temperature-controlled room between 14.00 and 16.00 hours on day 2. Both the calorimeter and the calibration room were maintained at 28° and the subject wore standard clothing of thin cotton shirt and trousers.

A meal consisting of 113 g Complan (Glaxo-Farley Food Ltd, Plymouth, Devon) mixed with water and 169 ml Lucozade (Beecham Products, Brentford, Middlesex) was given at 08.30 hours on day 1. The meal was identical to the three other meals given during the day such that each subject consumed 10·46 MJ (2500 kcal) during a 24 h period. The simple nature of the food allowed for accuracy in duplicating and speed of preparing the meals.

Table 2. *Outline of activity carried out by each subject while living in the calorimeter*

Postural activity	Period spent in each posture between 12.30 hours on day 1 and 12.30 hours on day 2 (h): Light activity session	Moderate activity session
Lying*	10·0	10·0
Sitting	12·5	10·5
Standing†	1·0	1·5
Cycling‡	0·5	2·0

* Between 22.30 hours on day 1 and 08.30 hours on day 2.

† 18.00–18.30 hours on day 1 and 08.30–09.00 hours on day 2 for light activity session; and 18.30–19.00, 22.00–22.30 hours on day 1 and 08.30–09.00 hours on day 2 for moderate activity session. Meals were at 08.30, 12.00, 16.00 and 19.00 hours.

‡ 1 N at 25 rev/min at 15.00–15.30 hours for light activity session; and 1 N at 50 rev/min at 15.00–15.30, 18.00–18.30, 21.30–22.00 hours on day 1, and 11.00–11.30 hours on day 2 for moderate activity session.

Meals were at 08.30, 12.00, 16.00 and 19.00 hours.

The subject was required to follow a programme of activity, while inside the calorimeter, which was designated as either a light or a moderate regimen. The two regimens are detailed in Table 2. The subject was otherwise able to read, write, telephone, listen to the radio or watch television. Each subject occupied the calorimeter for a minimum of one light regimen and one moderate regimen session. In addition, subject nos. 001–005 carried out the light regimen sessions in duplicate, and nos. 001–004 carried out the moderate regimen sessions in duplicate.

Measurement of HP inside the calorimeter

Two estimates of energy expenditure, total heat loss (HL) and HP, were made using a whole-body calorimeter 2·08 m long, 1·22 m wide and 1·95 m high. Details of the calorimeter and the method of calculating HL and HP have been published (Dauncey *et al.* 1978). Only the results for HP will be presented, since it is HP which the HR method aims to predict. The measurement of HL was checked before and after each 27 h session, using a standard heat source. Gas concentrations of air entering and leaving the calorimeter were measured using a paramagnetic analyser for oxygen and an infrared analyser for carbon dioxide. The gas analysers were calibrated before each 27 h session.

Measurement of HR inside the calorimeter

HR was measured using both a single channel SAMI (TEM Sales Ltd, Crawley, Sussex) and a Medilog miniature analogue tape recorder (Type 4-24, The Oxford Instrument Co. Ltd, Osney Mead, Oxford). Both these instruments are small and portable and of the type used in field studies.

The SAMI used an electrochemical E-cell to record the number of heart beats over long periods of time (Baker *et al.* 1967). When the recording was complete the number of heart beats was assessed with an E-cell replay machine (TEM Sales Ltd). The subject was instructed to use three E-cells in the calorimeter, so that HR could be obtained during the following periods: 12.30–22.30 hours on day 1, 22.30–08.30 hours on days 1 and 2, 08.30–12.30 hours on day 2. The tape recorder gave a continuous record of the electrocardiogram (ECG) (Littler *et al.* 1972; McKinnon, 1974). A standard cassette of magnetic recording tape (Philips C120) ran from 10.00 hours on day 1 until 12.30 hours on day 2. The casette was replayed on a playback deck (The Oxford Instrument Co. Ltd) which had been modified so that both a visual record of ECG on a chart recorder and the HR over selected periods of time could be obtained.

Two pairs of electrodes (V-trace, Abbott Laboratories, manufactured by NDM Corp., Dayton, Ohio, USA) were placed at the supra-sternal position and fifth intercostal space, and the sub-sternal and sub-axillary positions. A standard procedure was followed in the placing and fitting of the electrodes to ensure a minimum of skin resistance and a good recording of the heart beat. The site with an R-wave of at least 1 mV was found using an electrode placement test set (TEM Sales Ltd). The site was then cleaned and lightly abraded to remove the *stratum corneum*, and the electrodes were placed in position and checked to ensure that their impedance was less than 10 kΩ and preferably between 4 and 8 kΩ.

The SAMI and its E-cells were tested and calibrated with a pulse generator (calibration oscillator type 28S, TEM Sales Ltd). After this procedure, there was found to be no difference in the total number of heart beats recorded by the SAMI and the tape recorder over 24 h and the three shorter periods previously mentioned. Since almost identical results were obtained with the two systems for measuring heart-rate, only those relating to the tape recorder will be presented. Additionally, the tape recorder was used to obtain mean values of HR at 30 min intervals throughout the 27 h spent in the calorimeter; a facility not available from the SAMI.

Calibration of HR v. *HP*

Standard method, using the temperature-controlled room. In the first part of the study a calibration procedure similar to that employed by many workers was used, i.e. with one calibration point at a low level of energy expenditure, such as lying or sitting, and the remaining points during activity. Simultaneous measurements of HR and HP were made with the subject lying, sitting and standing quietly and then while cycling at four levels of work on a bicycle ergometer.

In the second part of the study measurements of HR and HP at higher work levels than those undertaken in the calorimeter were excluded. Instead, two measurements were made in the lying, sitting and standing positions. The first recordings were made while there was a minimum of movement while the second were made under more natural conditions, with the subject being encouraged to make small movements of the arms and legs. This movement was also intended to minimize the pooling of blood in the extremities. Additionally, measurements were made at the two levels of cycling which corresponded to those used in the calorimeter.

After the subject had been lying quietly for 1 h at 28° in the calibration room one set of electrodes was connected to an ECG recorder (Mingograf-803; Siemens-Elema AB, Solna, Sweden) and the subject started breathing into a mouthpiece connected to a Kofranyi–Michaelis (K–M) respirometer. A period of 5 min was allowed for HR and breathing to stabilize and simultaneous measurements of HR and HP were then made. Expired air (100 l) was sampled and analysed for O_2 and CO_2 with a Lloyd-Haldane apparatus. An alternative procedure involved the measurement of the volume of inspired air using a Parkinson Cowan dry gas meter and the expired air was analysed every 1 min for 15 min with a paramagnetic O_2 analyser (Type OA 272; Taylor Servomex Ltd, Crowborough, Sussex) and an infrared CO_2 analyser (Analytical Development Co. Ltd, Hoddesdon, Herts.). HR was measured throughout the period of gas collection. Further calibrations were made while the subject was standing quietly and then cycling at increasing levels of work. A period of 5–10 min was allowed for HR and breathing to stabilize between each activity.

Method using the calorimeter (method CAL). To provide a calibration which was more appropriate than the standard methods for obtaining the relation between HR and HP over a 24 h period, and to obtain calibration points over long periods of time and during sleep, results from one of the sessions inside the calorimeter were used. Mean values of HR and HP during four 5 h and one 4 h period were obtained; the time periods were: 12.30–17.30 hours, 17.30–22.30 hours, 22.30–03.30 hours, 03.30–08.30 hours and 08.30–12.30 hours. These periods were chosen so that they included not only sleeping but also a variety of activities in the standing and sitting positions. They also included the short periods of cycling so that the whole range of HR and HP could be used in the analysis.

Prediction of HP from HR

The extent to which energy expenditure could be predicted from HR in the calorimeter was examined using each of six methods. The predicted HP was then compared with the actual HP measured in the calorimeter. Using each method the energy expenditure was predicted for a 24 h period: 12.30 hours on day 1 to 12.30 hours on day 2; and also for the three time intervals previously mentioned.

Using standard calibration techniques

The predicted HP was always derived from calibration values obtained immediately after the subject left the calorimeter. Methods A–D used the method of least squares for obtaining the regression line of HR *v.* HP. Each regression equation was used for predicting 24 h HP from the mean 24 h HR.

Method A. The calibration points obtained while lying still and while cycling were used. Bradfield *et al.* (1971) and Poleman *et al.* (1972) used a similar method with the resting point obtained in the supine position.

Method B. This method used the calibration points obtained for sitting still and for cycling and was similar to one of the methods reported by Payne *et al.* (1971).

Method C. This method used the calibration points obtained while the subject was lying, sitting and standing still and was thus similar to the lower range of activity discussed by Booyens & Hervey (1960).

Method D. This method used the calibration points which were representative of the subject's activity while in the calorimeter (Warnold & Arvidsson Lenner, 1977) and therefore included all the calibration points for lying, sitting and standing, i.e. while still and while moving slightly, and that for cycling which corresponded to the level of work used in the calorimeter.

Method E. Whereas methods A–D used a straight line for the prediction of HP from HR, method E employed a logistic fit such that the curve was constrained to pass through the lower calibration points. The curve was fitted to all the points obtained during a single calibration session, except those for standing (because of the problem associated with blood pooling in the legs). A logistic curve was usually fitted:

$$y = d + \left(\frac{f}{1+ge^{-hx}}\right),$$

although an asymptotic exponential regression model had to be fitted when only two points for cycling had been obtained:

$$y = a + be^{kx},$$

where y was the dependent variable, x was the independent variable, and a, b, d, f, g, h and k were constants. For purposes of computational efficiency the curves were extrapolated to pass through two additional points at the lower end of the scale, where x was 20 or 40

Table 3. *Heat production (HP; absolute kJ) and heart-rate (HR, beats/min) of each subject while occupying the calorimeter at 28° from* 09.30 *hours on day* 1 *to* 12.30 *hours on day* 2

(Mean values are given for subjects who carried out sessions in duplicate)

Sessions* ... Subject no.†	Total (24 h)		Day 1 (10 h)		Night (10 h)		Day 2 (4 h)	
	HP	HR	HP	HR	HP	HR	HP	HR
				Light activity session				
001	7580	71	3600	78	2585	60	1395	81
002	7792	60	3721	62	2677	49	1394	79
003	8722	80	4366	84	2692	70	1664	94
004	10514	71	5105	74	3524	65	1886	81
005	9606	‡	4513	72	3286	‡	1807	71
006	7381	49	3524	52	2532	42	1324	56
007	9365	75	4401	75	3186	66	1778	99
008	9076	69	4312	74	3220	60	1544	79
				Moderate activity session				
001	8906	78	4628	86	2630	65	1648	88
002	8584	64	4257	69	2686	51	1641	83
003	9220	83	4803	91	2630	70	1787	97
004	11660	74	6064	79	3519	65	2079	86
005	10074	76	4932	82	3199	66	1943	88
006	8624	55	4310	60	2574	45	1740	66
007	10483	68	5152	72	3265	58	2066	84
008	9370	72	5103	78	2488	59	1779	88

* Total, 12.30 hours on day 1 to 12.30 hours on day 2; day 1, 12.30–22.30 hours; night 22.30 hours on day 1 to 8.30 hours on day 2; day 2, 08.30–12.30 hours on day 2.
† For details, see Table 1.
‡ Overnight record for HR incomplete.

beats/min and y was 4 kJ/min. Since the curve was non-linear a prediction of 24 h HP could not be made from the mean 24 h HR. Predictions of HP were made separately for each short period within which HR was constant and these were averaged to give 24 h predicted HP.

Using method CAL

For each subject, one session inside the calorimeter was used to obtain five calibration points to which a linear regression model of HR *v.* HP was fitted. The regression was then used for predicting HP during the other sessions in the calorimeter. Since the regression from each completed light or moderate activity session was used to predict the HP during the three other sessions, there was thus no bias in favour of using a calibration session at a given activity level to predict HP during a session at the same level of activity.

RESULTS

Energy expenditure and HR in the calorimeter

The duplicate sessions carried out by five of the subjects showed that there was no significant difference in 24 h HP between two sessions at the same level of activity ($P > 0·3$ for light regimen and $P > 0·8$ for moderate regimen).

The values of HP and HR for each subject while in the calorimeter are given in Table 3. A complete set of continuous measurements of both HR and HP in the calorimeter was not available for all subjects. This was due to inadequate contact of the HR electrodes. Although the SAMI was an easy and compact system for the subjects to use, the tape

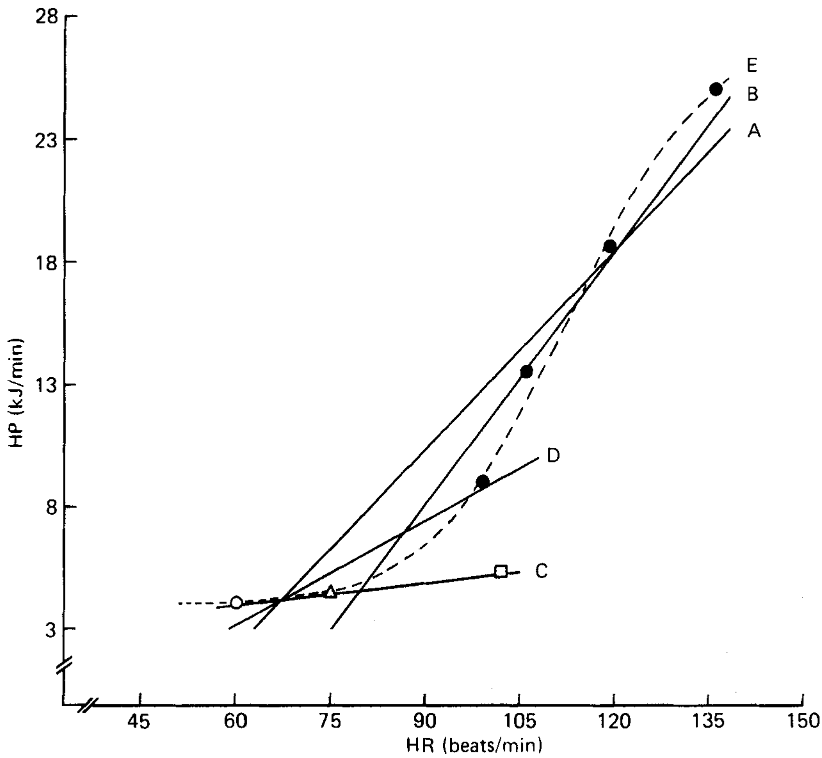

Fig. 1. An example of calibration results from subject no. 002. Standard techniques were used for measuring heart-rate (HR; beats/min) and heat production (HP; kJ/min) simultaneously over short periods of 10–15 min at several levels of activity. The HP in the calorimeter during the 27 h session of moderate activity immediately before the calibration was predicted from the mean HR (63 beats/min for the 24 h) using each of five methods. Methods A–D used a linear regression model while method E used a logistic model. Calibration points used for each method of prediction were: method A, lying still (○) and cycling (●); method B, sitting still (△) and cycling; method C, lying, sitting and standing still (□); method D, lying, sitting, standing still and cycling at the second lowest work load (which corresponded to the level of cycling used in the calorimeter); method E, all the points excluding that for standing. For details of procedures, see pp. 4–6.

recorder had the advantage of giving a continuous record which could be used for examining ECG.

As expected, HP during the 24 h of a moderate regimen session was always greater than that during a light regimen session. This was also the situation for the 24 h HR in all but one of the subjects. The higher values of HP and HR during the moderate regimen session were also observed during the daytime on both days 1 and 2, but at night, when there was presumably no difference in activity, there was no consistent difference in HP or HR.

Calibration of HR v. *HP*

Standard method. An example of results from one calibration session with subject no. 002 is given in Fig. 1 in which the linear regression lines for methods A–D are plotted, as well as the logistic curve for method E. Reference to the HR of subject no. 002 in Table 3 shows the difficulties which could be encountered by using a straight line for the prediction of HP, since the 24 h HR was at the lower end of the calibration.

To allow for comparison of the calibration results with those given by other workers,

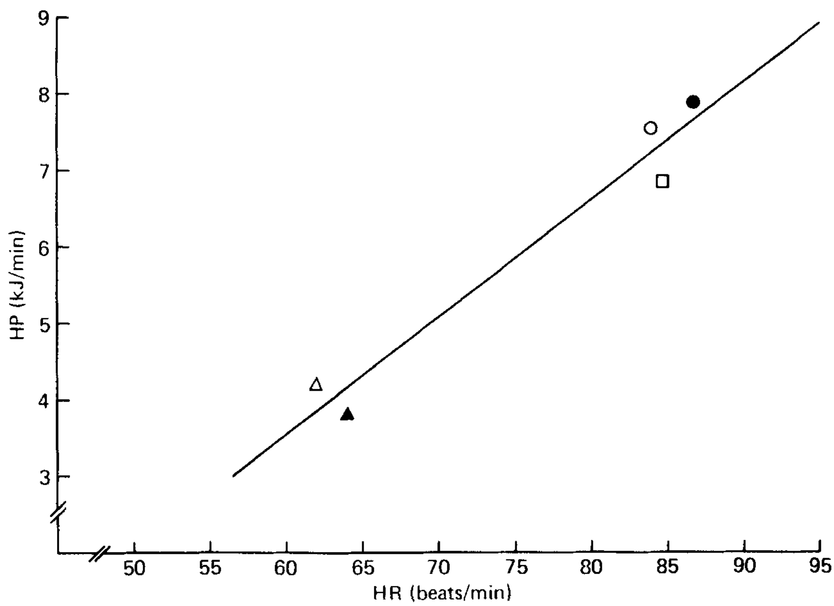

Fig. 2. An example of method CAL, the calibration with the calorimeter used for predicting heat production (HP; kJ/min) from heart-rate (HR; beats/min). The calibration points were taken from the first session of moderate activity in the calorimeter for subject no. 001 and represent the mean values for the following periods: ○, 12.30–17.30 hours on day 1; ●, 17·30–22.30 hours on day 1; △, 22.30–03.30 hours on days 1–2; ▲, 03.30–08.30 hours on day 2; □, 08.30–22.30 hours on day 2. The regression line was used for predicting the HP of subject no. 001 while in the calorimeter on three other occasions of either light or moderate activity.

Table 4. *Regression coefficients for the calibration of heart-rate (beats/min)* v. *heat production (kJ/min) for each of five methods of predicting heat production from heart-rate**

(Mean values and standard deviations for eight subjects)

Method of prediction	Postural activities	Regression coefficients: Slope Mean	Slope SD	Intercept Mean	Intercept SD
A	Lying and cycling	0·407	0·112	—22·6	8·7
B	Sitting and cycling	0·429	0·111	—24·2	6·8
C	Lying, sitting and standing	0·109	0·086	—2·2	5·7
D	Similar to those used in the calorimeter	0·233	0·080	—10·7	5·9
CAL	—	0·123	0·032	—2·3	2·3

A–D, Standard calibration procedures.
CAL, Calorimeter procedure for calibration.
* For details, see pp. 4–6.

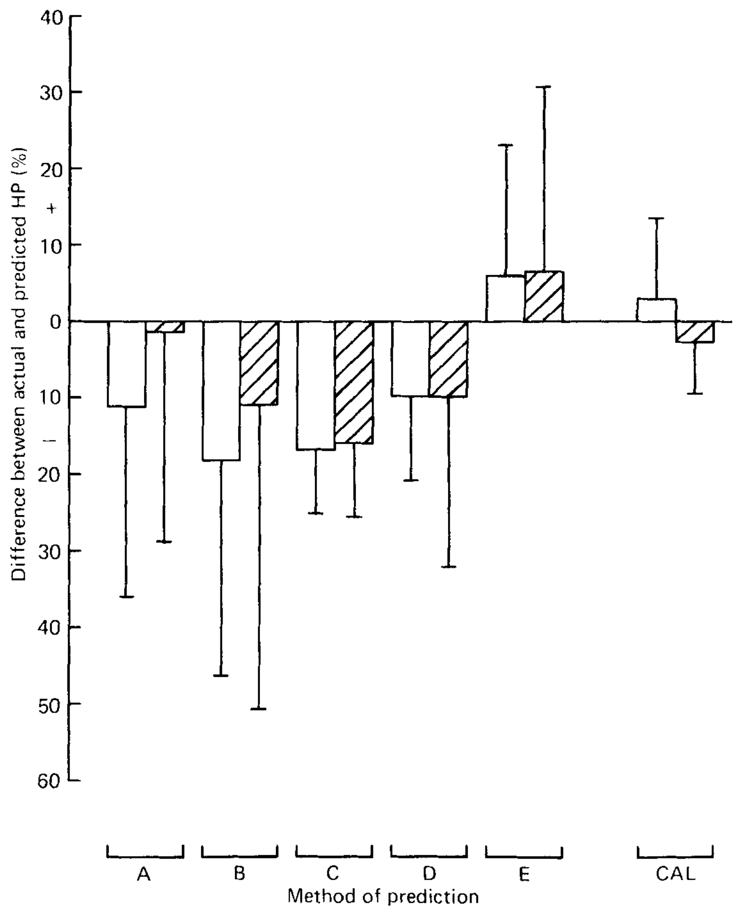

Fig. 3. Percentage differences between actual and predicted values for 24 h heat production (HP) (12.30 hours on day 1 to 12.30 hours on day 2) obtained using six methods of prediction (see Figs. 1 and 2), for both light (□) and moderate (▨) sessions of activity. The mean values and standard deviations, represented by vertical bars, for the eight subjects are given. CAL, Calorimeter method: for details of methods A–E and CAL, see pp. 4–6.

the regression coefficients for the standard methods of predicting HP from HR (methods A–D) are given in Table 4.

Method CAL. An example of the regression line obtained using method CAL is given in Fig. 2. In contrast with some of the standard methods, the points for all subjects gave a straight-line calibration which covered the range of mean 24 h HR values, since two points were obtained overnight when the subject was usually asleep. The mean regression coefficients are given in Table 4.

Comparison between actual and predicted values of HP

The percentage difference between the actual and predicted HP in the calorimeter for the eight subjects was calculated, using each of the six methods of prediction. Since the range of activity and hence the range of energy expenditure encountered in the study was very narrow, correlation coefficients tended to be misleading. For example, a perfect correlation could be associated with a large mean difference and standard deviation. A better assessment of the methods was obtained from the mean ($\pm$ SD) of the percentage difference.

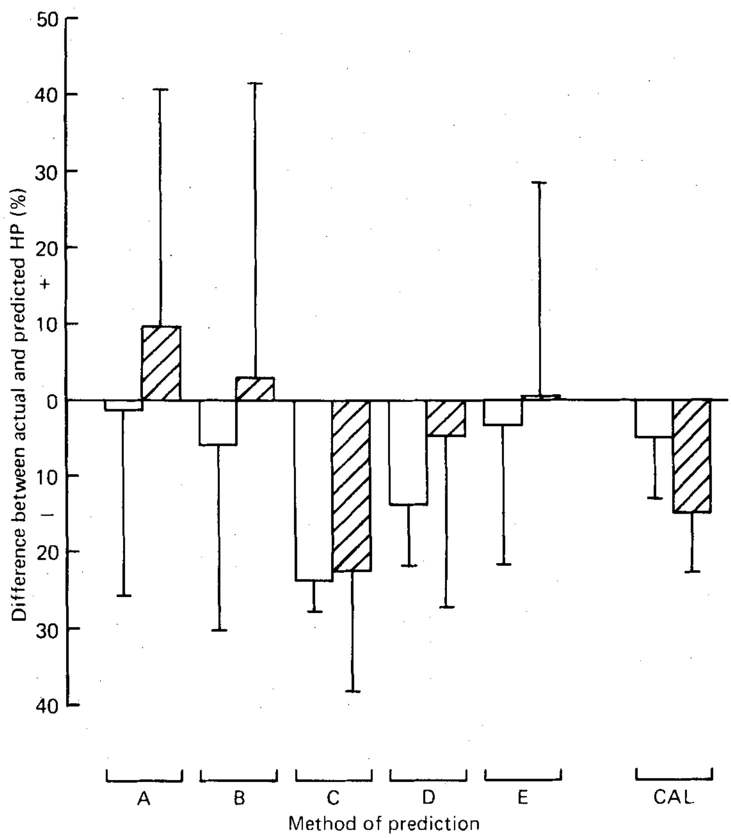

Fig. 4. Percentage differences between actual and predicted values for daytime heat production (HP) (12.30–22.30 hours on day 1) obtained using six methods of prediction (see Figs. 1 and 2), for both light (□) and moderate (▨) sessions of activity. The mean values and standard deviations, represented by vertical bars, for the eight subjects are given. CAL, Calorimeter method: for details of methods A–E and CAL, see pp. 4–6.

Twenty-four hour HP (12.30 *hours on day* 1–12.30 *hours on day* 2). Fig. 3 shows the mean (±SD) of the difference between the actual and predicted 24 h HP in the calorimeter, expressed as a percentage. The mean difference for the four standard methods of prediction (methods A–D) was −14% for the light regimen session and −9% for the moderate regimen session. However, the standard deviations were large, particularly for methods A and B. A prediction could be very accurate for one subject but give a large over-estimate or underestimate of HP for the next individual. For example, using method A for the light regimen session, the percentage differences for subjects nos. 001–004 were −15, −4, +25 and −58, respectively. Method C was more useful for estimating HP, since the standard deviation of the percentage difference was only ±8·3. The logistic curve (method E) gave a mean percentage difference of +6, but the standard deviation was again large. Method CAL gave a mean (±SD) difference of +3·1±10·5 for the light regimen session and −2·7±6·7 for the moderate regimen session. In the five subjects where at least two sessions were used for the predictions, the standard deviation for method CAL was reduced considerably: the mean (±SD) difference for the light and moderate regimen sessions respectively were 0·2±1·9 and 2·5±1·8%.

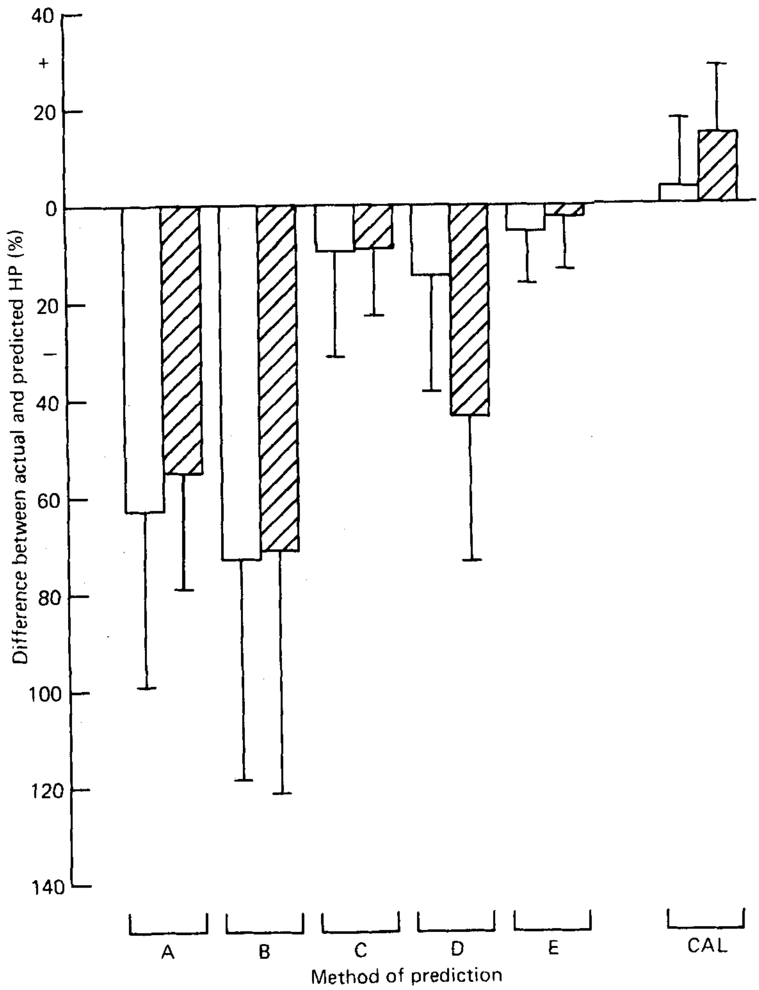

Fig. 5. Percentage differences between actual and predicted values for night-time heat production (HP) (22.30–08.30 hours on days 1–2) obtained using six methods of prediction (see Figs. 1 and 2), for both light (□) and moderate (▨) sessions of activity. The mean values and standard deviations, represented by vertical bars, for the eight subjects are given. CAL, Calorimeter method: for details of methods A–E and CAL, see pp. 4–6.

Daytime (12.30–22.30 *hours on day* 1) *and night-time* (22.30–08.30 *hours on days* 1–2) *HP*. Examination of Figs. 4 and 5 shows the marked difference in the prediction of HP using standard techniques, when determined during the day as compared with the night. During the day, although there were again large standard deviations for methods A and B, the mean differences were less than 10%. But at night, these two methods underestimated HP by a mean of between 55 and 74%. Method C, which used the lower activity points of the calibration, gave a better prediction of HP during the night, while the standard deviation was again low during the day. The logistic curve (method E) gave a difference of approximately 5% during both the day and night, while method CAL tended slightly to underestimate the HP during the day and over-estimate the night-time HP.

DISCUSSION

Using the standard methods of prediction which employ one calibration point at rest and a series of calibration points at several levels of activity, it was found that the 24 h energy expenditure of individuals could not be predicted from HR with any acceptable extent of accuracy. This was mainly because the relation between HR and HP was linear using the standard calibration procedure only at energy expenditures greater than approximately 10 kJ/min. The relation seemed less close at the levels of HP or HR which are usually encountered during a sedentary or moderately active day.

The mean 24 h HR in the calorimeter was 70 beats/min with a range of 60–91 beats/min during the daytime of the moderate regimen session. This was in agreement with the findings of many workers, who seldom reported mean HR values of more than 90 or 100 beats/min even in active subjects. Booyens & Hervey (1960) found HR values of less than 90 beats/min in five subjects of normal weight during lying, sitting and standing, while Bradfield & Jourdan (1972) reported daily HR values of between 81 and 93 beats/min in six obese women. In addition, Poleman *et al.* (1972) suggested that a Filipino farmer might rest for 8 h of the day during the slack season, at an HR of 50 beats/min, and work for 2 h at an average of 100 beats/min. The standard methods of prediction therefore tend to be inappropriate for those subjects who are not involved in long periods of physical activity. For example, Bradfield & Jourdan (1972) obtained calibration curves for obese women before and after weight loss at HR values of 75–90, 110–125 and 130–145 beats/min, yet the mean daily HR was between 81 and 98 beats/min.

In contrast with the present study, other workers have been unable to compare their estimates of HP with an accurate measurement of the actual HP. Warnold & Arvidsson Lenner (1977) compared their predictions with estimates of energy intake and body composition. Poleman *et al.* (1972) also compared their predictions with estimates of energy intake (a method which can be appropriate only when the subject is in energy balance). Poleman *et al.* (1972) found that the HR method over-estimated energy expenditure in Filipino men by more than 50% whereas in the women they were in error by +9%. They suggested that the difference between the men and women was an environmental one; the men tended to work for long periods in the heat which resulted in an increase in HR without a concomitant increase in HP. In addition, Poleman *et al.* (1972) were unable to obtain reliable estimates of the most important point in the calibration, the resting HR.

The standard methods of prediction, as customarily used, would therefore appear to be of use only for those individuals who are engaged in continuous physical activity. If the daily activities include periods of immobility, blood pooling in the peripheries could alter the relation between HR and HP. This is probably unusual and the problem is more likely to occur during the standard calibration procedure. In the second part of the study using the standard calibration, where the subject was encouraged to make small movements in all three postures, there was a change in the relation between HR and HP. The change on standing was particularly striking, with a marked decrease in HR and a small increase in HP. This change could be due to an increase in the venous return and the stroke volume of the heart. The effect on Fig. 1, which excludes the points obtained while the subject was moving slightly in each of the three postures, would be to bring the series of points closer to a linear relation. It may be possible to use the standard method for very large populations, where only a mean value for energy expenditure is required. However, accuracy of an equivalent extent could probably be obtained from a well-informed estimate based on an account of each subject's activity.

It is to be expected that a method of prediction which uses a number of points at low levels of activity or a curve fitted to several points at low activity would tend to give a better prediction of energy expenditure than methods A–B. This was indeed the situation with methods C–E. Ideally, for those investigations where the subjects are sedentary, numerous calibration points should be obtained in each of the positions of lying, sitting and standing, at several levels of activity. However, this would make the method impractical for many clinical and field studies since it can take 2 h to obtain only two calibration points for each of four postural activities.

The present study has indicated the potential value of a new method of calibration (method CAL) which uses a whole-body calorimeter. If a respiratory chamber proves to be satisfactory for calibrating subjects then it may become an essential part of a study on energy expenditure in the community. Fig. 2 indicates that it may be possible to obtain a suitable linear regression of HR *v*. HP if the subject is calibrated over long periods in the less restricted environment of a chamber. To determine whether a linear or curvilinear regression is more appropriate would require a sophisticated analysis of short-term changes in HR and HP. This in turn would require that rapid changes in HP could be determined within a large respiratory chamber by a method similar to that suggested by McLean & Watts (1976). Meanwhile, it should be recognized that current procedures for calibrating subjects may lead to large errors and every attempt should be made to calibrate individuals in circumstances similar to those for which estimates of energy expenditure are needed.

The authors thank Mr P. R. Murgatroyd, Miss H. L. Davies and Mr J. A. Crisp for their invaluable assistance; Mr T. J. Cole for computing advice; Mr D. Brown, ARC Statistics Group, Cambridge, for suggesting the use of the logistic curve and for statistical advice; the volunteers who took part in the study; and Professor L. E. Mount and Dr B. A. Cross, FRS, for enabling them to carry out the work at Babraham.

REFERENCES

Andrews, R. B. (1971). *Am. J. clin. Nutr.* **24**, 1139.
Baker, J. A., Humphrey, S. J. E. & Wolff, H. S. (1967). *J. Physiol., Lond.* **188**, 4P.
Berg, K. (1971). *Am. J. clin. Nutr.* **24**, 1438.
Booyens, J. & Hervey, G. R. (1960). *Can. J. Biochem. Physiol.* **38**, 1301.
Bradfield, R. B. (1971). *Am. J. clin. Nutr.* **24**, 1148.
Bradfield, R. B., Chan, H., Bradfield, N. E. & Payne, P. R. (1971). *Am. J. clin. Nutr.* **24**, 1461.
Bradfield, R. B. & Jourdan, M. (1972). *Am. J. clin. Nutr.* **25**, 971.
Brockway, J. M. & McEwan, E. H. (1969). *J. Physiol., Lond.* **202**, 661.
Dauncey, M. J. & James, W. P. T. (1977). *2nd International Congress of Obesity*, Washington, DC, USA.
Dauncey, M. J., Murgatroyd, P. R. & Cole, T. J. (1978). *Br. J. Nutr.* **39**, 557.
DuBois, D. & DuBois, E. F. (1916). *Archs. int. Med.* **17**, 863.
Goldsmith, R., Miller, D. S., Mumford, P. & Stock, M. J. (1966). *J. Physiol., Lond.* **189**, 35P.
Littler, W. A., Honour, A. J., Sleight, P. & Stott, F. D. (1972). *Br. Med. J.* **3**, 76.
McKinnon, J. B. (1974). In *Biotelemetry II. 2nd International Symposium*, p. 67 [P. A. Neukomm, editor]. Basel: S. Karger.
McLean, J. A. & Watts, P. R. (1976). *J. Appl. Physiol.* **40**, 827.
Metropolitan Life Insurance Company (1960). *Stat. Bull.* **41**.
Payne, P. R., Wheeler, E. F. & Salvosa, C. B. (1971). *Am. J. clin. Nutr.* **24**, 1164.
Poleman, T. T., Beeghly, W., Matlon, P. & McGregor, A. (1972). *Cornell int. Agric. Dev. Mimeogr.* **38**.
Warnold, I. & Arvidsson Lenner, R. (1977). *Am. J. clin. Nutr.* **30**, 304.
Webster, A. J. F. (1967). *Br. J. Nutr.* **21**, 769.
Wooley, J. B. & Owen, R. B. (1977). *Comp. Biochem. Physiol.* **57A**, 363.
Yamamoto, S., Matsuoka, K., Yamada, H. & Mimura, K. (1977). *Jap. J. Zootech. Sci.* **48**, 138.

Printed in Great Britain