A LONGITUDINAL STUDY TO ASSESS THE CURRENT FIELD TECHNIQUES FOR MEASURING ENERGY BALANCE IN MAN

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ABSTRACT. A longitudinal energy-balance study was performed on six members of the British Antarctic Survey to assess the accuracy of techniques currently used in the measurement of food intake and energy expenditure.

Three methods were used to measure food intake:

i. Weighed inventory method, with subsequent computation using the food composition tables of McCance and Widdowson (1960).
ii. 24 hr. dietary recall. Values were also calculated from food composition tables.
iii. Collection of a duplicate of the total day's intake. Samples were directly analysed by bomb calorimetry and corrections were made for faecal and urinary energy losses.

Daily energy expenditure was measured by three techniques:

i. Prediction from mean 24 hr. heart rate.
ii. From diary-card records of activity and determination of the energy cost of these activities using the Kofrányi-Michaelis respirometer.
iii. As for (ii) but substituting literature values for the cost of the various activities.

The duplicate sample with direct analysis was used as the standard against which the other two food intake methods were assessed. The weighed inventory method overestimated direct analysis by 6 per cent but this can be reduced further if fatty foods and composite dishes are avoided. The recall method underestimated by 16 per cent. This was found to be due to subjects forgetting foods which they had eaten and also incorrect assessment of portion size.

The standard used to assess the expenditure methods was calculated from the change in body-energy stores throughout the year. A heart-rate method overestimated the standard by 3 per cent, whilst the diary-card methods underestimated by 6 per cent using measured values and 11 per cent using literature values. No one method was best for all subjects.

A short assessment of the nutrient content of the base diet and field rations is also included.

THE potential energy consumed by the living organism is required for metabolic processes within the body, thermoregulation and the performance of work. When the energy taken into the body is of the same magnitude as that which is expended, then the organism is in energy balance. If, however, the intake is greater or less than expenditure, a state of imbalance exists which is reflected in an increase or decrease in body fat and eventually body weight. Nutritional problems in energy metabolism involve the balancing of energy intake and expenditure and, although there has been much research into the field of human energy balance, it still remains a controversial subject.

Balance studies in animals have revealed that regulation of energy balance is achieved by a control of food intake (Adolph, 1947). However, this does not apply to humans who can override such controls with good food, good company or monetary rewards. Miller and others (1967) showed in experiments in which students were fed 1,000 kcal./day, in excess of their base-line energy intake, that their weight increase was much smaller than the theoretical value calculated from the excess energy consumed. They also demonstrated that, whilst the students were in the overfed state, the energy cost of a standard task was greater than when they were on the base-line diet. Whether balance is controlled by intake or expenditure of energy, the length of time over which this control operates is also of interest. Although Edholm and others (1955) found a correlation between mean daily energy expenditure and mean daily intake 2 days later, it is generally agreed that there is no direct relationship between intake and expenditure over at least a week and Garrow (1973) was sceptical that a biological control exists at all.

This controversy concerning energy balance may, to a large extent, be due to the techniques which are used in its measurement. Blaxter (1956), in a review on energy balance, suggested that errors greater than 0·5 per cent are undesirable for its measurement. Very few techniques possess such precision. Besides errors in the methods, it is also difficult to maintain full subject co-operation during a long-term study. The procedures necessary for measuring intake and expenditure may interfere with a subject's work and his social life, e.g. weighing all the food which he consumes and wearing a respirometer which inhibits speech and food consumption, and can also cause embarassment when worn in public.

During the past 15 years heart rate has been used by work physiologists to predict energy expenditure over various periods of time (Berggren and Christensen, 1950; Malhotra and others, 1963; Goldsmith and others, 1967). Development of miniature portable heart-rate recording devices has made it possible to measure energy expenditure with very little, if any, inconvenience to the subject.

The object of this study was to see how well Man controlled his energy balance during a year and by using a variety of techniques for measuring food intake, energy expenditure and energy balance it was possible to assess the errors involved in the measurement of the various parameters.

The Antarctic provides ideal conditions for such a study. One is able to observe a small captive community, members of which have a wide range of energy expenditure, do not have an active social life and can be studied intensively for periods of at least a year.

METHODS

Observations were made on six members of the British Antarctic Survey at Halley Bay (lat. 75° 36′ S., long. 26° 39′ W.) during 1972. Table I presents the physical characteristics

TABLE I. PHYSICAL CHARACTERISTICS OF THE SUBJECTS

Subject number	*Height* (cm.)	*Average weight* (kg.)	*Age* (yr.)	*Occupation*
4	189·3	71·90	24	Nutritionist
5	178·9	64·88	21	Cook
6	173·9	67·86	26	Electrician
9	177·0	68·26	24	Ionosphericist
10	182·7	78·36	21	Meteorologist
12	175·8	70·53	22	Ionosphericist
MEAN	177·8	70·30	23	

of the subjects. Five were studied for 1 week in every month for a total of 10 months and the sixth made continuous daily measurements for a total of 316 days. Two subjects were studied per week, during which time food intake and energy expenditure were measured using three different methods. Energy balance was measured by one method and estimated from the intake and expenditure methods.

Food intake

Energy intake was measured using three techniques:

i. Weighed inventory method.
ii. Collection of a duplicate of the total day's intake.
iii. 24 hr. recall.

These methods have been well reviewed by Becker and others (1960) and Marr (1971), and therefore only a brief description is warranted. Dietary spring balances were provided so that subjects could weigh each individual food item prior to its consumption. Any waste was weighed and subtracted from the original weight of the food. At the end of each week the dietary information was prepared for computer analysis. This involved numbering the different food items with a code number. The code numbers corresponded to those which

McCance and Widdowson (1960) used to number foods in their food composition tables. Upon returning to the United Kingdom the code numbers and the respective weights of the foods for each day were fed into the computer. The output data gave each day's energy intake and the mean daily intake for the week (Miller and Mumford, 1970).

On 1 day during the week an exact duplicate of all the food eaten by the subject was weighed out and collected. It was homogenized, weighed and a sample taken for direct analysis in the ballistic bomb calorimeter (Miller and Payne, 1959) which gives a measure of the gross energy (GE) of the food. However, since not all of this is available to the body, it was corrected for energy losses in the urine and due to incomplete digestion using the formula of Miller and Payne (1959):

$$ME = 0{\cdot}95GE - 0{\cdot}075N \text{ per cent},$$

where ME = metabolizable energy,
GE = gross energy as measured by the bomb calorimeter,
N = nitrogen content of the day's intake.

The day following the duplicate sample collection, the subject was given a dietary recall card and was requested to write down the quantities of all that he had eaten during the previous 24 hr. The cards were subsequently analysed by dietitians (trained in their analysis) who calculated the daily energy intake.

Energy expenditure methods

Heart rate

The prediction of an individual's daily energy expenditure from his mean 24 hr. heart rate depends upon the existence of a linear relationship between these two parameters. Under many conditions this linear relationship does exist for an individual but not for groups (Bradfield, 1971*a*). Hence heart rate and energy expenditure of an individual must be measured simultaneously during a series of standard exercises of increasing intensity so that a regression equation can be calculated. The standard exercises must range from a basal or resting level to one which is expected to exceed the individual's "usual" maximal expenditure (Bradfield, 1971*b*). Heart rate was measured using S.A.M.I. (Baker and others, 1967) and energy expenditure using the Kofrányi-Michaelis (1940) respirometer. During each week that a subject was studied he performed the following series of exercises:

i. Lying for 30 min.
ii. Sitting for 30 min.
iii. Stepping up and down a 9 in. step at six steps a minute for 20 min.
iv. Stepping up and down a 9 in. step at 12 steps a minute for 20 min.
v. Stepping up and down a 9 in. step at 24 steps a minute for 20 min.

These exercises covered a range of expenditures from 4·2 to 33·5 kJ/min. and a range of heart rates from 45 to 170 beats/min. Occasionally values of 42 to 52 kJ/min. were recorded during the year, but such expenditures rarely lasted any great length of time.

Energy expenditure and heart rate were also measured each day during the week, for about 30 min., whilst the subject went about his everyday tasks.

By using all the heart-rate data it was possible to calculate five different regression equations and hence predict five different daily energy expenditures for each individual. Table II presents the data used for each regression equation.

Energy expenditure was also estimated by the more conventional diary-card method. There were four basic activities, i.e. lying and sleeping, standing, sitting and walking (inside base), which were allocated the abbreviations L, St, S and W, respectively. Space was provided for other activities which were given different numbers and against which the subject wrote a description of the activity. During the week the energy cost of each activity was determined over periods of approximately 10 min. using the Kofrányi-Michaelis (1940) respirometer.

The information recorded in the diary cards was used again using values from the literature, after they had been corrected for body weight. Where possible, values were taken from those of Passmore and Durnin (1955) and Durnin and Passmore (1967). Values of activities peculiar

TABLE II. DESCRIPTION OF THE DATA FOR THE HEART-RATE/ENERGY-EXPENDITURE REGRESSION EQUATIONS

HEART-RATE METHOD:

1. Weekly regression equations obtained from the standard exercise measurements.
2. A single annual regression equation using all the standard exercise points obtained throughout the year.
3. A single annual regression equation using all the habitual activity points obtained during the year.
4. Weekly regression equations using weekly standard exercise and weekly habitual activity points.
5. A single annual equation using all the points from (2) and (3) above.

to the Antarctic were taken from Brotherhood (1973, personal communication). Table III lists the literature values used corrected for a 70 kg. man. It also lists the mean values obtained in this study corrected for a 70 kg. man.

Energy balance

At the beginning and end of each week skin-fold measurements were taken at the four sites suggested by Durnin and Rahaman (1967) using Harpenden skin-fold calipers (Tanner and Whitehouse, 1955). The subjects also weighed themselves every morning after emptying their bladders. Using these values, it was possible to calculate the body-fat changes during each week that the subject was studied. Whilst the errors involved in this procedure over as short a time as a week may be large, by taking the mean values at the beginning and end of the year the error in calculating body-fat changes is small (Acheson and others, in press).

With a knowledge of food intake and energy balance it is possible to calculate energy expenditure by using the formula:

$$EE = FI - B,$$

where EE = mean daily energy expenditure,
FI = mean daily food intake corrected for the error revealed by direct analysis,
B = mean daily energy balance (in kJ).

RESULTS

The results of the food-intake data are summarized in Table IV. It can be seen that when the weighed inventory data are compared with that of bomb analysis it overestimated direct analysis by approximately 6 per cent, whilst the 24 hr. recall method underestimated by 16 per cent.

When all the data were analysed statistically using the paired "t" test, both weighed inventory and 24 hr. recall were significantly different from direct analysis, $P = 0{\cdot}00005$ and $P = 0{\cdot}00001$, respectively. There was, however, a good correlation between the weighed inventory and direct analysis values ($r = 0{\cdot}91$; $P < 0{\cdot}00001$) which suggests that the values obtained by weighing can be corrected.

Although the mean error for the weighed inventory method was +6 per cent, 2 days gave errors of as much as +30 per cent. By comparing the computer results with those of direct analysis of individual items which made up the day's diet, it was found that composite dishes and fatty foods were responsible for these large discrepancies. Similar observations have been made by Stock and Wheeler (1972). Approximately one-third of the error could be accounted for by differences in water content of the same dish prepared on different occasions and the remainder was due to the variable fat content of various foods.

The mean annual energy intake corrected for the 6 per cent error shown by direct analysis was $12{\cdot}9 \pm 1{\cdot}8$ MJ/day ($3{,}079 \pm 440$ kcal./day) and the proportion of energy supplied by fat, carbohydrate and protein was 32·7, 56·3 and 11 per cent, respectively. This is very

TABLE III. ENERGY-EXPENDITURE VALUES OF VARIOUS TASKS TAKEN FROM THE LITERATURE AND MEAN VALUES OBTAINED IN THIS STUDY
(Values corrected for 70 kg. man)

Task	*Literature values* (kJ/min.)	*Values from this study* (kJ/min.)
Standing	8·5	9·7
Sitting	6·3	6·3
Walking (2·5 m.p.h.)	15·4	19·5
Showering	12·3	18·6
Clearing up room	19·6	18·0
Sitting working	8·7	8·0
Washing crockery	14·0	13·4
Washing clothes	14·0	15·5
Making bed	19·6	21·4
Sweeping	11·7	21·8
Mopping	17·6	27·7
Hoovering	20·5	20·5
Sewing	6·8	5·6
Typing	7·2	8·4
Climbing ladders	33·8	30·3
Carrying food boxes (40–80 lb.)	28·0	42·6
Sawing wood	28·4	20·2
General woodwork	17·6	15·4
Painting	11·4	13·8
Paint spraying	17·6	15·7
Paint stripping	18·5	18·1
Working at lathe	8·5	10·6
Working on electrical equipment	10·4	14·1
Tractor repairs	18·5	17·4
Skiing and ski-walking	32·5	34·1
Ice chipping	37·8	26·2
Shovelling snow	32·5	40·3
Playing darts	17·6	14·9
Playing table tennis	17·6	23·1
Physical exercise	28·0	35·5
Crevasse probing	11·3	14·4
Tractor driving	23·4	13·4
Driving Sno-cat	9·5	15·0
Cooking	14·0	13·5
Peeling potatoes	9·7	10·3

TABLE III—*continued*

Task	*Literature values* (kJ/min.)	*Value from this study* (kJ/min.)
Inside		
Dragging snow drums	31·7	37·2
Clearing snow from main tunnel	28·2	21·5
Hammering nails	20·2	24·6
Sledge building	13·1	15·9
Driving radar	7·0	10·3
Cable-laying in lofts	16·2	19·8
Cable-laying in tunnels	19·9	11·9
Developing films	7·0	10·6
Outside		
Riding in vehicle	14·0	6·2
Driving Foxtrac Skidoo	13·7	15·1
Starting Skidoo	19·0	28·0
Walking in snow	33·4	31·4
Fuel run	31·9	35·1
Dump raising	37·5	32·4
Bolting hut frames	13·0	23·2
Removing refuse from base (outside gash)	25·1	22·4
Erecting ionosonde aerials	22·0	20·8
Cable-laying outside	15·8	34·7
Dog-feeding	29·9	30·5
Field expeditions		
Breaking camp	32·2	26·7
Pitching tent		
Outside man	31·9	26·3
Making camp		
Inside man	17·7	16·3
Manhauling	51·9	47·3
Belaying	18·6	14·4
Ski-joring	17·2	22·3
Dog-sledging	31·4	28·5
Carrying loads outside	46·9	47·8
Riding sitting on sledge	13·4	13·2
Riding standing on sledge	16·1	27·6

TABLE IV. MEAN DAILY ENERGY INTAKES OBTAINED BY THREE DIFFERENT METHODS

Subject	*Weighed inventory* (kcal.)	(MJ)	*24 hr. recall* (kcal.)	(MJ)	*Direct analysis* (kcal.)	(MJ)	*Number of observations*
4	3,372	14·11	2,627	11·00	3,120	13·06	15
5	2,296	9·61	2,013	8·43	2,239	9·37	5
6	3,020	12·64	2,112	8·84	2,971	12·44	9
9	3,194	13·37	2,049	8·58	2,830	11·85	10
10	3,797	15·89	3,425	14·34	3,642	15·25	9
12	2,467	10·33	2,153	9·01	2,391	10·01	4
MEAN	3,024	12·66	2,397	10·03	2,866	12·00	52
Error	+158	+0·66	−469	1·97			
Percentage error	+5·5		−16·4				

similar to that of a typical West European diet. During field trips the mean energy intake fell slightly to 12·6±0·7 MJ/day (3,003±178 kcal./day) and there was an increase in the proportion of fat and protein (40 and 12·5 per cent, respectively) at the expense of carbohydrate, 47·5 per cent. The reduced energy intake and increased expenditure was reflected by a loss of body weight which generally returned to the pre-trip level within a week after returning to base.

Energy expenditure

The assessment of energy expenditure was more difficult as no one method could be assumed to be correct. However, by using the mean daily energy expenditure obtained from the corrected mean daily energy intake and the change in energy stored during the year, it was possible to assess the heart-rate and diary-card methods.

Table V presents the mean daily energy expenditure for the group estimated from five different heart-rate/energy-expenditure regression equations, two diary-card methods and from energy balance.

For the group it can be seen that a heart-rate method gave the lowest error, +3 per cent. But when results are considered individually no one method was best for all subjects. Both diary-card methods underestimated energy expenditure. The diary card/measured values underestimated by 6 per cent, whilst using literature values almost doubled the error.

The mean daily energy expenditure for the year estimated from energy balance was 13·0±1·8 MJ/day (3,108±424 kcal./day). During 56 man-days of field trips the mean expenditure was 14·8±2·6 MJ/day (3,545±620 kcal./day). This value is lower than might be expected due to at least 12 man-days being spent at rest due to bad weather. Mean values recorded on a combined Skidoo and manhaul trip were approximately 16·7–19·0 MJ/day (4,000–4,500 kcal./day).

Energy balance

Table VI illustrates the calculation of mean daily energy balance from body-weight and skin-fold thickness measurements taken at the beginning and end of the year. The mean daily intake and expenditure for the group mentioned above (12·9 and 13·0, respectively) indicates that the group was in negative energy balance. This is supported by four subjects

TABLE V. COMPARISON OF MEAN DAILY ENERGY EXPENDITURE OBTAINED FROM HEART-RATE AND DIARY-CARD DATA WITH THAT DETERMINED FROM ENERGY BALANCE

Method	*Mean daily energy expenditure* (MJ)	(kcal.)	*Error* (MJ)	(kcal.)	*Percentage error*
Energy balance	13·00	3,108	–	–	–
Heart rate 1	15·69	3,749	2·69	641	20·6
Heart rate 2	15·94	3,809	2·94	701	22·6
Heart rate 3	13·42	3,207	0·42	99	3·2
Heart rate 4	14·30	3,417	1·30	309	9·9
Heart rate 5	14·41	3,443	1·41	335	10·8
Diary card 6	12·29	2,935	−0·71	−173	−5·6
Diary card 7	11·68	2,791	−1·32	−317	−10·2

who exhibited a decrease in their body-energy stores. The remaining two were in positive energy balance throughout the year. The mean values for intake and expenditure suggest that balance is regulated precisely during the year (0·1 MJ/day which is approximately equivalent to 1 kg. of body fat per year). Individually, this was not the case; subject 4 lost the most energy, 120·9 MJ (28,890 kcal.) and subject 6 gained the most, 84·3 MJ (20,130 kcal.) during the year. These energy changes, however, were far less than those estimated from daily energy intake and expenditure.

DISCUSSION

The errors involved in taking duplicate samples are very small. However, the method is tedious and expensive. The results of the weighed inventory method gave a mean error of +6 per cent, which can be decreased considerably if composite dishes and fatty foods with a variable fat content are avoided. The dietary recall card proved very inaccurate, especially as the subject had been consciously weighing out and recording the food the day before. By comparing the recall cards with the day's intake, it was found that generally at least one food item was omitted and that the subjects invariably underestimated portion sizes. Whilst recall cards may give an idea of the pattern of daily food intake, they are not sufficiently accurate for energy-balance studies.

Measurement of heart rate proved acceptable to both investigator and subjects, whilst diary cards were regarded with less enthusiasm since they required regular marking.

Of the heart-rate methods, it is of interest to compare methods 1 and 3. Method 1 regression equations were derived from a series of standard exercises which were performed each week. Method 3 represents a single annual regression equation based on expenditure measurements of the subject's habitual activities. Unfortunately, it was not possible to construct weekly regression equations from habitual activities as the range of expenditures was small and the correlation coefficients poor.

Although standard exercises give regression equations with high correlation coefficients, it appears that they do not give acceptable estimations of habitual energy expenditure. Weekly regression equations derived from habitual activity measurements may be accurate for the prediction of 24 hr. energy expenditure, provided that a range of expenditures can be performed which give regression equations with correlation coefficients sufficiently high for predictive purposes.

Estimation of mean daily energy expenditure from food intake and the change in energy balance during the year was by far the most convenient. Improvements in techniques for

TABLE VI. CALCULATION OF MEAN DAILY ENERGY BALANCE AND EXPENDITURE FROM BODY WEIGHT AND SKIN-FOLD THICKNESS MEASUREMENTS AT THE BEGINNING AND END OF THE YEAR

Subject	*Body weight* (kg.; t_o)	*Percentage body fat* (t_o)	*Weight body fat* (kg.; t_o)	*Body weight* (kg.; t_n)	*Percentage body fat* (t_n)	*Weight body fat* (kg.; t_n)	*Body fat* (g.; t_n–t_o)	*Balance* (kJ; 37·67 × fat)	*Number of days* (n)	*Balance* (kJ/day)	*Food intake corrected*	*Mean 24 EE* (MJ)
4	74·84	17·24	12·90	70·71	13·71	9·69	−3,210	−120,934	346	−350	13·939	14·289
5	67·30	15·08	10·15	62·31	12·70	7·91	−2,240	−84,264	320	−263	10·164	10·427
6	66·31	15·35	10·18	69·45	17·91	12·44	+2,260	+85,143	336	+253	12·520	12·267
9	68·85	17·58	12·10	68·53	15·35	10·52	−1,580	−59,609	311	−192	13·081	13·273
10	77·12	17·10	13·19	79·34	17·55	13·92	+730	+27,662	256	+108	15·626	15·518
12	70·93	19·20	13·62	68·99	16·90	11·66	−1,960	−73,866	262	−282	11·993	12·275
										MEAN	12·9	13·0

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measuring body composition and body fat would enable energy expenditure to be calculated accurately over shorter periods than a year. This would eliminate time-consuming measurements of daily expenditure which require continuous recording of either heart rate or activities in a diary card. All that would be necessary is an accurate record of daily intake, which only occurs two or three times during the day, and an accurate measure of body fat at the beginning and end of the study period.

Although the main purpose of this study was an energy-balance survey, it was also possible to assess the nutrient content of the base diet and sledging rations. The mean daily nutrient intakes for subject 4 are given in Table VII. Also shown are the recommended daily intakes (Davidson and others, 1972) and the national average nutrient intakes (Ministry of Agriculture, Fisheries and Food, 1970). The base diet was more than adequate in all nutrients except for thiamine, which was marginally low. A large supply of vitamin supplements was available on the base. These were taken regularly by the men and it is unlikely that anyone was consuming less than the recommended daily nutrient requirement. However, during the field trips there was generally a fall in nutrient intake; all except Vitamin C and thiamine were at acceptable levels. It is not known whether Vitamin D is required by the adult but sufficient would be synthesized in the skin by the action of ultra-violet light on 7-dehydrocholesterol.

Vitamin C and thiamine were almost half the recommended allowances but these were augmented by the vitamin pills which were taken daily. Although Orr (1965) suggested that the Vitamin C content can be increased in powdered milk and potatoes in the sledging ration, vitamin pills, providing that they are taken, are far more convenient and less expensive.

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TABLE VII. MEAN DAILY NUTRIENT INTAKE

	Protein (g.)	*Vit. A* (mg.)	*Vit. B* (mg.)	*Vit. C* (mg.)	*Thiamine* (mg.)	*Riboflavine* (mg.)	*Nicotinic acid* (mg. equiv.)	*Fe* (mg.)	*Ca* (mg.)
Base diet (subject 4)	103·1	2,666	4·9	59	1·08	1·9	17	25	1,280
Field rations (subject 4)	106·3	714	1·0	17	0·70	2·2	16	15	1,520
cf. recommended daily intakes (men 18·35 yr.) (1972)									
Moderately active	75·0	750	2·5	30	1·20	1·7	18	10	500
Very active	90·0	750	2·5	30	1·40	1·7	18	10	500
cf. national average (1970)	75·8	4,670	3·2	52	1·30	1·8	15	14	1,040

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