The effect of environmental temperature and humidity on 24 h energy expenditure in men

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The effects of environmental temperature and humidity and their interaction on 24 h energy expenditure were measured using whole-body indirect calorimetry in eight normal-weight young men who wore standardized light clothing and followed a controlled activity regimen. A randomized-block experimental design was used, with temperature effects assessed by measurements at 20, 23, 26 and 30°, while humidity was altered from ambient (50–65 % relative humidity) to high (80–93 % relative humidity) at 20 and 30° only. There was no significant effect of humidity on 24 h energy expenditure at the two extreme temperatures in this range, though when periods of sleep and exercise were excluded the energy expenditure at high humidity was significantly higher than that at ambient humidity ($P < 0.02$). The effect of temperature at ambient humidity levels showed lower values at 23 and 26° than at 20 and 30° ($P < 0.02$). The effect of temperature was not equally apparent in all components of the 24 h energy expenditure, as sleeping metabolic rate and the energy cost of walking and cycling showed no significant effect of temperature over this range. This raises the possibility that the effects of temperature are attributable to behavioural changes during the waking portion of the day rather than any non-shivering thermogenic mechanisms at tissue level.

Temperature: Humidity: Energy expenditure

Energy expenditure and heat production in man and animals are known to vary with environmental conditions (Blaxter, 1989). Although there is extensive information on energy expenditure in relation to environmental temperature in animals (e.g. Davis *et al.* 1973; Close & Mount, 1978; Valencia *et al.* 1980), there is more limited information on the effects of humidity and temperature on energy expenditure in man under conditions other than those experienced in extreme environments. Three studies of energy expenditure in women (Dauncey, 1981; Blaza & Garrow, 1983; Lean *et al.* 1988) and another in men and women (Warwick & Busby, 1990) showed an increase in energy expenditure on mild cold exposure, while no effect of relative humidity changing from 32 to 66% has been found on resting metabolic rate (RMR) in men and women (Nielsen, 1987). The purpose of the present study was to extend the information on the effect of environmental temperature, humidity and their interaction on 24 h energy expenditure in young men over a range of temperature and humidity likely to reflect some of the differences between tropical and temperate climatic zones.

METHODS

Subjects

The subjects were eight healthy young men ranging in age from 22 to 44 years and in body mass index (BMI) from 19·6 to 26·3 kg/m^2. Subject characteristics are given in Table 1. All subjects were weight stable and maintained their normal pattern of diet and activity during

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Table 1. *Subject characteristics*

Subject no.	Age (years)	Height (H) (m)	W (W) (kg)	W/H² (kg/m²)	Fat* (%)
1	33	1·66	63·0	22·8	18·1
2	29	1·65	60·5	22·1	10·2
3	41	1·83	71·0	21·2	16·3
4	35	1·88	77·0	21·8	17·8
5	38	1·88	69·4	19·6	12·0
6	44	1·66	67·2	24·4	19·5
7	39	1·75	80·5	26·3	26·1
8	22	1·69	64·0	22·4	16·6
Mean	35	1·75	68·4	22·4	16·6
SE	2·5	0·03	2·2	0·8	1·7

* Calculated as percentage of body-weight from the sum of four skinfolds (Durnin & Wormersley, 1974).

a 3-week period, except during the days when 24 h energy expenditure was measured, when their diets were strictly controlled.

Diets

The diets given during the 24 h calorimeter measurements provided 1·55 times the measured basal metabolic rate (BMR) for each subject, with 55% of the energy as carbohydrate, 30% as fat and 15% as protein. Three meals of the same energy content and nutrient composition were given.

Anthropometric measures

Body-weight was measured to the nearest 50 g using an electronic scale with an accuracy of 1/3000 (DS-410; Teraoka Seiko Co. Ltd), before breakfast and after voiding, with the subjects wearing a light cotton t-shirt and trousers. Height was measured to the nearest 1 mm with a Holtain stadiometer. Fat-free mass was estimated from the measurement of four skinfolds according to Durnin & Womersley (1974).

Calorimetry

BMR was measured once for each subject by indirect calorimetry using a ventilated hood system with a Scheme Engineering vortex flowmeter and Servomex oxygen (series 1100) and carbon dioxide (PSA 402) analysers (McNeill *et al.* 1988). Room temperature was maintained above 25° during the measurements.

Energy expenditure (24 h) of each subject was measured on six occasions separated by at least 48 h. Measurements were made in two indirect calorimeter chambers, each measuring 14·5 m³ and containing a bed, table, chair, toilet, wash basin, TV, telephone and bicycle ergometer. The walls and ceilings of the chambers were made from white insulated material and the floors were carpeted. Each subject carried out all six measurements in one chamber only. Details of the technical operation of these chambers have been described elsewhere (McNeill *et al.* 1989). Atmospheric air was pushed into the chamber at a rate of about 140 l/min and recirculated within the chamber by a commercial air-conditioning system which also maintained the air temperature. Relative humidity was calculated from measurement of dew-point temperature made by a dew-point hygrometer (Michell Instruments, Cambridge) and temperature by digital thermistors. Energy expenditure is calculated for every 10 min period by the formula of Weir (1949). A 'fast-response' calculation programme which takes account of gas volumes retained in the chamber, similar to that described by McLean & Watts (1976), is used to infer instantaneous rate of energy expenditure of the subject from the rate of change of gas concentrations of the chamber air. This programme was used to calculate the sleeping metabolic rate (SMR), defined as the energy expenditure between midnight and 06.00 hours (excluding the periods in which an ultrasound transmitter–receiver operating on the doppler principle showed significant movement of the subject). The exclusion of the periods from 22.30–24.00 and 06.00–07.30 hours from the estimation of SMR is designed to eliminate data from periods in which the subjects frequently found difficulty in sleeping. Values for SMR are, however, given for an 8 h period, to give an assessment of the likely magnitude of any effects on energy requirements. The energy expenditure of programmed physical activity (PEE) was calculated as energy expended during the six 30 min periods of walking or cycling (see below). Remaining energy expenditure (REE) was calculated as 24 h energy expenditure – (SMR + PEE).

Chamber environmental conditions

Temperature in the chambers was controlled to within ±0·3° during the measurement at each of the six environmental settings which are shown in Table 2. High humidity conditions were created by means of two commercial humidifiers, while ambient humidity was that of atmospheric air at each of the selected temperatures. At 20° none of the subjects reported any conscious shivering, although some noticed piloerection.

Air movement in the chamber was controlled by the air-conditioning unit and was the same at all six environmental conditions. Wind velocity was measured by a thermal anemometer independently in both chambers in order to detect possible differences due to different locations of air inlets and outlets. Wind velocity measured at twenty-four different points in each chamber and divided into two cross-sectional areas showed no difference between chambers. Wind velocity measurements at each of the points were quite variable, so the data were analysed by the non-parametric Mann–Whitney–Wilcoxon rank sum test. Median values were 0·038 (Confidence Interval (CI) (95%) = 0·013 – 0·073) and 0·064 (CI (95%) = 0·025 – 0·127) m/s in chambers 1 and 2 respectively: this difference was not statistically significant.

Chamber activity protocol

In each measurement of 24 h energy expenditure the subjects spent 4 h becoming acclimatized to the temperature and humidity conditions before the actual recording began. The measurement was then made for a further 24 h, during which activity was strictly controlled. Subjects got up at 07.30 hours and went to bed at 22.30 hours. In between these times the subjects were asked to sit on the bed or at a table, except during three cycling periods and three walking periods of 30 min each. The cycling was performed on a Monark ergometer (Mod. 818 E) at a work load of 1 kP at 30 rev./min, equivalent to 30 W. Walking periods were regulated with a metronome set at 80 beats/min walking at one step per beat on flat ground.

Clothing

Clothing for the subjects was standardized to light cotton suits. A single cotton sheet and heavy cotton bedspread were provided for cover at night.

Body temperature

In two subjects body temperature was measured using urine temperature as an indicator of deep body temperature. Subjects inside the chamber voided urine directly into a thermos flask, initially filled with water at 37°. On the first void the subjects discarded the water and immediately voided into the flask and recorded the temperature with a digital temperature

Table 2. *Chamber environmental conditions during 24 h runs for normal-weight young men*
(Values are means with their standard errors over each 24 h run for the eight subjects)

Environmental condition	Temperature (°)		Relative humidity (%)	
	Mean	SE	Mean	SE
20 H	20·0	0·10	88·6	1·7
20 A	20·0	0·10	65·6	2·2
23 A	23·2	0·10	52·6	0·9
26 A	26·3	0·10	52·6	0·9
30 A	30·4	0·07	51·8	2·8
30 H	30·2	0·14	84·4	1·8

probe. This urine was then left in the flask until the next void, when it was discarded immediately before the subsequent collection.

Statistical analysis

The effects of temperature, humidity and the interaction of temperature and humidity were assessed by randomized-block analysis of variance with a factorial structure, using the Genstat statistical analysis program. The standard error of the treatment means was calculated as $\sqrt{(RMS/n)}$, where RMS is the root mean square from ANOVA, and n is the number of subjects. Effects of temperature and humidity were assessed by pair-wise comparisons. The t values were calculated as the difference between the means of the two pairs of treatments divided by the standard error of the treatment means. The effect of temperature was assessed by comparing the mean of the measurements at 23 and 26° with that of the measurements at 20 and 30°, all at ambient humidity, while the effect of humidity was assessed by comparing the mean of the measurements at ambient humidity at 20 and 30° with that of the measurements at high humidity at the same temperatures.

The effect of climatic conditions on body temperature, as assessed by urine temperature in two subjects, was assessed by a two-way analysis of variance, blocking by subject.

Ethical considerations

The protocol for the study was approved by the Joint Ethical Committee of Grampian Health Board and the University of Aberdeen, and all subjects gave informed written consent to participate.

RESULTS

The environmental conditions obtained for the chamber experimental runs are presented in Table 2. Humidity was a little more variable between the different runs than intended, due to differences in ambient humidity on the measurement days. However, the difference between the high and ambient humidity conditions at both 20 and 30° was greater than 20% relative humidity for all subjects.

Table 3 shows the individual values for 24 h energy expenditure at each of the six environmental conditions. Mean values for 24 h energy expenditure were lowest at 26° and increased both above and below this temperature. There were marked differences between subjects, so the data were analysed using a two-way analysis of variance. From this analysis the standard error of the treatment mean was 141 kJ (df 35). At both 20 and 30° the 24 h energy expenditure was a little higher at high humidity compared with ambient humidity

Table 3. *24 h energy expenditure (kJ/d) at six environmental conditions* for eight normal-weight young men*

Subject no.	Environmental condition ...	20H	20A	23A	26A	30A	30H
1		10270	9313	10026	9718	9669	10269
2		10749	11024	10668	10498	12031	11397
3		11810	11155	10729	11341	11311	11998
4		11018	10457	10171	9501	10371	9801
5		12932	12249	12707	11782	11897	12342
6		9201	9474	8849	8987	9377	9574
7		11835	11997	11771	11856	12309	12326
8		10071	10113	9276	9257	10031	9964
Mean		10986	10723	10525	10368	10874	10959
SE		418	383	445	412	407	418

* For details, see Table 2, and p. 321.

Table 4. *Mean values for sleeping metabolic rate (SMR) and energy expenditure of programmed physical activity (PEE) at six different environmental conditions* for eight normal-weight young men*

(Mean values with their standard errors)

	SMR (kJ/8 h)		PEE (kJ/3 h)	
Environmental condition	Mean	SE	Mean	SE
20H	2162	58	2582	189
20A	2142	59	2631	147
23A	2174	76	2564	161
26A	2183	58	2524	100
30A	2245	70	2607	152
30H	2227	76	2565	135

* For details, see Table 2 and p. 321.

levels, although this effect was not significant (t 1·23, $P = 0·23$). The effect of temperature on 24 h energy expenditure was more marked, with values at 23 and 26° significantly lower than those at 20 and 30° (t 2·49, $P = 0·02$).

A different pattern was observed in the SMR and PEE values (Table 4). The standard error of the treatment means from the two-way analysis of variance was 32 kJ for SMR and 55 kJ for PEE. SMR was lowest at 20° and highest at 30°, with those at 23 and 26° being intermediate between the values at the two extreme temperatures, although the temperature effect was not statistically significant (t 0·48, $P = 0·63$). There were very small differences between SMR at high and ambient humidities at both 20 and 30°, and the humidity effect was also not significant (t 0·03, $P = 0·98$). PEE showed no clear-cut effect of temperature (t 0·27, $P = 0·79$) or humidity ($t = 0·16$, $P = 0·87$). This suggests that the major effect of temperature on 24 h energy expenditure occurred during the daytime period at times other than the 3 h spent cycling and walking. This effect is illustrated in Fig. 1.

Urine temperatures measured in subject nos. 6 and 7 were not significantly different under the six environmental conditions (F 0·67, $P = 0·66$) (Table 5), suggesting that core temperature was maintained over this range of environmental conditions.

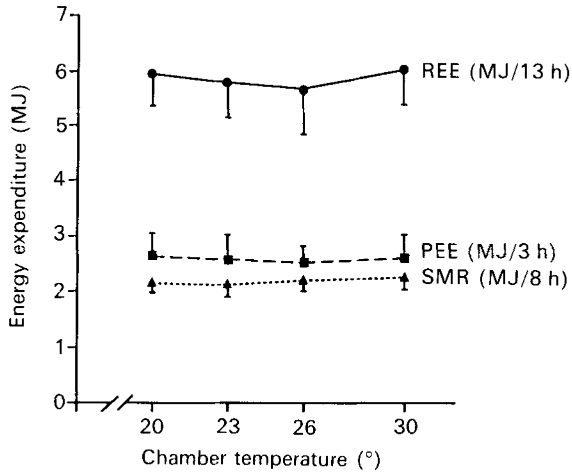

Fig. 1. The effect of chamber temperature on the components of 24 h energy expenditure for normal-weight young men: sleeping metabolic rate (SMR), the energy cost of programmed exercise (PEE), and residual energy expenditure (REE). Values as means and 1 SD represented by vertical bars. For details of experimental procedures, see pp. 320–321.

Table 5. *Urine temperature at different environmental conditions* for two normal-weight young men*

(Mean values and standard deviations)

	Urine temperature (°)		No. of urine voids	
Environmental condition	Mean	SD	Subject no. 6	Subject no. 7
20H	36·13	0·89	9	7
20A	36·29	0·95	8	8
23A	35·97	0·74	9	8
26A	36·00	0·75	11	5
30A	36·56	0·76	6	5
30H	36·39	0·41	8	8

* For details, see Table 2 and p. 321.

DISCUSSION

The present study is the first report of changes in 24 h energy expenditure above and below thermal neutrality in a group of male subjects. The increase in 24 h energy expenditure seen below 26° in the present study is similar to, if a little smaller than, the findings of Dauncey (1981) and Blaza & Garrow (1983) in women, and that of Warwick & Busby (1990) in men and women. The study by Dauncey (1981) showed a significant increase in heat production of 7% on changing the temperature from 28 to 22° in nine normal-weight women. Blaza & Garrow (1983) studied the difference in heat loss in five lean and five obese women between temperatures at the upper (25·0–28·0°) and lower (22·0–24·5°) extremes of individually selected thermal-comfort zones, and found that heat loss was on average 7·1% higher at the lower extreme than at the upper extreme in the lean women, but 5·8% lower at the lower extreme than the higher extreme in the obese women.

The lack of effect of temperature on SMR in the present study is different from the significant increase in RMR seen in five men at temperatures below 28° by Wilkerson *et al.*

(1972) and from the increase in SMR seen in the six normal-weight women studied by Lean *et al.* (1988). It is also different from Dauncey's (1981) measurements of RMR and Warwick & Busby's (1990) measurements of overnight metabolic rate. Dauncey's (1981) RMR determined in a 1 h period immediately after waking showed a mean increase of 11·3 % at 22° compared with 28°, while Warwick & Busby (1990) showed that the difference between overnight metabolic rate (24.00–08.00 hours) at 28 and 20° was of similar magnitude to the difference in daytime metabolic rate (08.00 – 24.00 hours), i.e. 4·5 %. The reason for this difference is not clear, since our subjects had opportunity for behavioural changes such as curling up but no opportunity to increase the level of insulation with extra bed clothing, while Warwick & Busby's (1990) subjects were given an ample supply of bedding from which to choose their preferred level of cover during the night at both temperatures.

The energy expended in programmed physical activity of cycling and walking was not influenced by temperature in the present study, and this agrees with Dauncey's (1981) finding of very little difference in energy expenditure in cycling at 22° compared with 28°. Although the work load used in the present study cannot be considered strenuous, it appears that the extra heat production associated with this moderate exercise was sufficient to compensate for any difference in thermal conditions.

From these measurements it is impossible to assess whether the changes in energy expenditure seen on mild cold exposure are due to non-shivering thermogenesis mechanisms, or due to changes in behaviour due to minor physical discomfort at the lower and higher temperatures leading to increased restlessness. The fact that in the present study the major effect of temperature was seen in the non-sleeping, non-active periods of the day implies that the latter possibility should not be excluded.

At temperatures above thermal neutrality there is little information on 24 h energy expenditure in man, but the possibility of an increase in energy expenditure at high temperatures is raised by the work of Consolazio *et al.* (1960, 1961). In military personnel performing light activities in a desert environment with temperatures in the region of 40°, energy intake was found to be about 4 MJ/d above predicted energy requirements (Consolazio *et al.* 1960). The increase in 24 h energy expenditure seen between 26 and 30° in our subjects is consistent with the suggestion of the latter authors that energy expenditure increases at high environmental temperatures due to the additional work of sweating and perhaps other effects. The possibility that an increase in environmental temperature has a significant effect on energy requirements in subjects regularly exposed to these temperatures is, however, questioned by a recent study showing a gradual decline in 2 h energy expenditure at 34° in young men over a period of 10 d of acclimatization (Garby *et al.* 1990).

Information on the effect of environmental humidity on energy expenditure in man at different temperatures is restricted to measurements of RMR (Nielsen, 1987) or to studies of the energy cost of specific activities under extreme conditions (e.g. Wenzel, 1978). Nielsen (1987) found no effect of acute changes in relative humidity from 32 to 66 %, although an earlier publication from the same group indicated that there could be a small decrease in 24 h energy expenditure over the range 15–51 % relative humidity (Garby *et al.* 1986). Wenzel (1978), working on a wide range of environmental temperatures and relative humidities, found that the highest heart rates resulted from increases in both temperature and humidity. No increase in heart rate was seen at low temperatures or with dry air at room temperature.

A more indirect approach to studying the effect of climate on energy expenditure was adopted by Quenouille *et al.* (1951) who combined data on BMR from many subjects from different parts of the world with different meal annual temperature and humidity. This analysis showed that there was a tendency for BMR to increase with increasing humidity and decreasing temperature. Because of the opposing effects of temperature and humidity in this analysis, it was concluded that in areas where temperature and humidity are either both high or both low, BMR will differ very little from that in areas with more moderate climate.

In the present study, analysis of variance of the measurements at 20 and 30° provided no evidence that relative humidity had a significant effect on energy expenditure over the range tested. However, the small differences between the high and low humidity runs does not rule out the possibility that humidity tends to increase energy expenditure by an amount too small to be significant with the small numbers of subjects studied here, or that more extreme relative humidities than those achieved in the present study could have some effect on energy expenditure.

The implications of these findings for energy requirements of free-living subjects are difficult to assess, since under normal conditions behavioural responses such as clothing, shelter from wind and changes in intensity of physical activity etc. would be expected to reduce the effects of climatic variations. Information on the effective thermal environment of individuals, as opposed to measurements of external climatic conditions, might help to assess whether the effect of temperature and possibly humidity on energy expenditure should be taken into account in attempts to establish the energy requirements of different populations. At present no consideration of the effect of climatic conditions on energy expenditure of populations is advised by Food and Agriculture Organization/World Health Organization/United Nations University (1985): the authors consider that in the present state of knowledge this is appropriate but that further studies are required to explore the possibility that in certain situations the climatic environment may have considerable effects on the energy requirements of free-living human subjects.

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