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ROLES OF SUBCUTANEOUS FAT AND THERMOREGULATORY REFLEXES IN DETERMINING ABILITY TO STABILIZE BODY TEMPERATURE IN WATER

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SUMMARY

1. The lowest water temperature in which different young adults could stabilize body temperature was found to vary from 32 °C to less than 12 °C, because of large differences in both total body insulation and metabolic heat production.

2. Total body insulation per unit surface area, in the coldest water allowing stability, was quite closely determined by mean subcutaneous fat thickness measured ultrasonically ($r = 0{\cdot}92$), regardless of differences in distribution of this fat between men and women.

3. Reactive individuals developed high metabolic rates, and often rather high insulations in relation to fat thickness, which enabled them to stabilize their body temperatures in water more than 10 °C colder than was possible for less reactive individuals of similar fat thickness.

4. Measurements of heat flux, after stabilization in the coldest water possible, showed that the trunk was the main site of heat loss and that over half of the internal insulation there could be accounted for by subcutaneous fat; by contrast, fat could account for less than a third of higher insulations found in muscular parts of the limbs, and for less than 3 % of very high insulations in the hands and feet.

5. After stabilization of body temperature at rest in the coldest possible water, exercise reduced internal insulation only in muscular parts of the limbs. Exercise also increased heat loss elsewhere by exposing skin of protected regions such as flexural surfaces of joints. During exercise total heat production increased rather more than heat loss in unreactive subjects, but less than loss in subjects whose heat production had already risen to a high level when they were at rest in cold water.

6. In warm (37 °C) water, tissue insulations were lower and much more uniform between subjects and between different body regions than in the cold. Even in the warm, however, insulations remained rather higher in fat than thin subjects, higher at rest than during exercise, and usually higher in the limbs than the upper trunk.

INTRODUCTION

These experiments were designed to assess the factors which determine the lowest temperatures of the body surface at which different people can stabilize their deep body temperatures. It has been widely realized that fat people tend to lose heat less rapidly than thin people in cold surroundings (e.g. Baker & Daniels, 1955; Pugh & Edholm, 1955; Carlson, Hsieh, Fullington & Elsner, 1958; Keatinge, 1960; Buskirk, 1966; Jequier, Gygax, Pittet & Vanotti, 1974; Holmer & Bergh, 1974; Hayward, Eckerson & Collis, 1975; Petrovsky & Lind, 1975; Smith & Hanna, 1975; Wade, Dacanay & Smith, 1979). In some circumstances fat can be the only important factor determining net heat exchange. In particular, the rates at which body temperatures of young adult volunteers fell in water at 15 °C were quite closely related to the reciprocals of the individuals' subcutaneous fat thicknesses (Keatinge, 1960). However, a limited number of experiments on selected fat and thin men showed that fat, at least as measured by skinfold calipers, was not the only important determinant of heat exchange when water temperature was varied to find the lowest water temperature in which body temperature could be stabilized (Cannon & Keatinge, 1960). A lower limit was set by cold vasodilatation, which prevented even unusually fat people from stabilizing in water much colder than 12 °C. Even in less cold water, skinfold thickness was not closely related to the lowest water temperatures in which four comparatively thin men could stabilize. We recently observed an extreme example, of a subject who cooled progressively with no significant metabolic response or awareness of cold in water as warm as 29 °C (Hayward & Keatinge, 1979). Similar insidious hypothermia was found in divers during routine work in the North Sea in which the standard heating system, which involves flooding the suit with water warmer than the surrounding sea, was used (Keatinge, Hayward & McIver, 1980).

The present experiments were designed primarily to assess the local and general factors which determine the ability of young men and women to stabilize body temperature at a safe level in water below body temperature, using new methods which avoid errors involved in earlier methods for measuring local fat thickness and heat flow. Fourteen adult volunteers were repeatedly immersed to find the coldest water in which each could stabilize deep body temperature. When stability was reached in that water exercise was started, and other experiments were made in warm water, to see the effects respectively of muscular activity and of cutaneous vasodilatation on overall and regional heat exchanges. The subjects were a self-selected and apparently a representative group of young adults normally engaged mainly in indoor activities with light or moderate physical exertion. One had also undergone recent exposures to cold, and one physical training, during recreational activities. Additional information about the subjects' regional heat losses in relation to fat thickness, which allows prediction of the minimum and maximum external temperatures at which body temperature can be stabilized by people of given fat thickness with given patterns of external insulation, is provided in the Appendix.

METHODS

The subjects were medical students, nurses, laboratory technicians, and one policeman, aged 18–27 yr, who volunteered for the experiments. Only one of them (M3) had had marked exposure to cold (as regular cox of a rowing eight in air usually below 0 °C) during the 8 weeks before the experiments. Another (M2) was in a high state of physical training, mainly from rowing. The subjects were first given a medical examination, and height and weight were measured. Subcutaneous fat thickness was measured by an ultrasonic apparatus (Wells Krautkramer), as the distance between skin surface and the junction of subcutaneous fat with tissue underlying it. The measurements were made at three sites on each of ten regions of the body, listed in Table 1. The three sites for each region were chosen as the most representative for that region, on the basis of approximately 200 ultrasonic measurements previously made in preliminary experiments on each of ten men and ten women (not subjects of the present experiments) by Mr M. Asalam (personal communication); those measurements also showed the amount, usually small, by which mean fat thickness of each region differed from the mean thickness measured at the three sites. The factors accordingly used to correct for this difference are shown in Table 1. The surface area of each of these regions in each subject was calculated from linear measurements on each subject, using the formula of Dubois & Dubois (1916) with additional subdivision of the arm area into upper arm and lower arm; the area of the upper arm was taken as 0·84 × distance from tip of clavicle to medial epicondyle of humerus × (circumference of arm just below axilla + circumference just above elbow). The area of the lower arm was taken as 0·84 × distance from medial epicondyle of humerus to styloid process of ulna × (largest circumference of forearm + smallest circumference at wrist). A small correction factor was then applied to all areas for each subject to allow for the fact (see Results) that their sum slightly underestimated total surface area, calculated from height (H) in cm and weight (W) in kg as $0{\cdot}007184 \times W^{0{\cdot}425} \times H^{0{\cdot}726}$ (Dubois & Dubois, 1916). Mean subcutaneous fat thickness of each subject was calculated by multiplying the surface area of each body region by the fat thickness measured for the region in this way, and dividing the sum of these products by total surface area.

Before each immersion experiment the subject was fitted with heatflow bands, safety rope, goggles to keep water out of the eyes, and e.c.g. leads. Male subjects wore bathing trunks and female subjects a two-piece bathing costume. The e.c.g. leads were attached to the right shoulder and at the fifth left intercostal space in the midclavicular line; the e.c.g. was displayed on a monitor throughout the experiment. The subject then climbed into a tank of water 3·5 m long and 1·3 m wide and deep, and sat on a slatted wooden seat at a level which immersed him or her up to the neck. A spray of water was directed over the head to simulate immersion of the head as well. Water in the tank was circulated by driving compressed air through three ducts in the water which directed streams of water at approximately 1 m/sec at the subject from different directions. Readings were then made until rectal temperature was stable, defined as a change of less than 0·025 °C in fifteen minutes, or until it fell below 35 °C in which case the experiment was discontinued. If the temperature stabilized, full measurements of heat production and regional losses were made, and after these the subjects started work against water resistance, making backwards and forwards movements 0·32 m each way with the hands, and pedalling with the legs on unloaded bicycle pedals with circular movements of 0·5 m circumference as close as possible to a frequency set by a metronome at 50 Hz. Resistance was increased by a rubber flipper 400 mm long and 120 mm wide attached to each pedal. The movement was therefore mainly in the limbs, but involved trunk muscles concerned in movements of the shoulders and hips; there was also considerable associated movement of all parts of the body. Exercise was continued and readings made for at least 30 min except in one case (subject F1) when the experiment had to be discontinued after 20 min because body temperature fell below 35 °C. In the other subjects, the metabolic rate (with allowance for respiratory heat loss) and the rate of change of body temperature during the second 15 min of exercise were used to calculate total body insulation during exercise; the lowest water temperature in which each could have stabilized body temperature at the same level during such exercise with these values of metabolic rate and insulation was then calculated. After the experiments the subjects were rewarmed in a hot bath at 42 °C until body temperature had risen to 36·5 °C.

Such experiments were repeated in water which was 3–4 °C warmer or colder than in the last experiment until the lowest water temperature was found in which the individual could stabilize body temperature; the results of the experiments at that water temperature are those reported in this paper. When individuals could stabilize in water at 12–13 °C this was taken as the lowest water temperature allowing stability at rest or in exercise, since previous studies showed that in colder water cold vasodilatation developed and caused progressive falls in body temperature in even the fattest subjects (Cannon & Keatinge, 1960). A further experiment of a similar pattern was made on each subject, first still and then exercising, in warm water at 37 °C (±0·5) °C; in this case exercise was continued until body temperature stabilized.

Body temperature was measured to the nearest 0·025 °C by a rectal thermistor inserted 100 mm (Light Laboratories; 99 % response time < 30 sec). Metabolic rate was determined from expired air collected in a plastic bag for accurately timed periods of 5–10 min. The percentage of oxygen in the bag was determined immediately by a paramagnetic analyser (Beckman E2) and its volume by a dry gas meter (Gallenkamp GF 095). Metabolic rate was calculated by the method of Weir (1949) from the oxygen deficit and the volume of the gas corrected to S.T.P.

When subjects were in a state of heat balance (rectal temperature changing less than 0·025 °C in 15 min) total body insulation per unit surface area was calculated directly from the measured metabolic rate with allowance for respiratory heat loss, and from the difference between rectal temperature and the temperature of the water surrounding the subject. It was previously shown that temperatures of exposed parts of the surface of the skin fell to within 0·3 °C of water temperature within 20 min of immersion in stirred water at 15 °C (Keatinge, 1959). Respiratory heat loss during cold immersions was calculated on the assumption that expired air was at 37 °C

TABLE 1. Sites of measurement of regional subcutaneous fat thickness by ultrasound, and calculation of mean thickness for each region

	Places of measurement on each region at midpoint (vertically) of each region except head			Factor multiplied by fat thickness at $A+B+C$ to give mean regional thickness	
Region	A	B	C	Men	Women
Head	Anterior (forehead)	Above pupil of eye	Above ear	0·301	0·323
Trunk					
Upper third	Antero-lateral	Lateral	Postero-lateral	0·325	0·506
Middle third	Anterior*	Antero-lateral	Lateral	0·339	0·341
Lower third	Anterior*	Antero-lateral	Lateral	0·363	0·364
Thighs	Anterior	Lateral	Posterior	0·341	0·339
Lower legs	Antero-medial	Postero-medial	Lateral	0·348	0·358
Feet	Anterior	Medial	Lateral	0·338	0·321
Upper arms	Anterior	Medial	Posterior	0·375	0·330
Forearms	Anterior	Lateral	Posterior	0·338	0·326
Hands	Anterior	Lateral	Posterior	0·339	0·347

* 20 mm from mid line.

and saturated with water vapour (Christie & Loomis, 1932), and that inspired air had been saturated with water vapour at 22 °C and was at the temperature of the surrounding water when inspired. The inspired gas was drawn from outside the room and passed through a metal tube in the immersion tank to bring it to water temperature before it was inhaled. When calculating whole body insulation for subjects whose deep body temperature was not stable, a further allowance was made for loss or gain of stored heat assuming body tissues to represent 64 % of total body mass and to have a specific heat of 0·83 (Burton, 1935).

Local heat losses were measured by flexible heat flow bands whose edges were attached to the skin by adhesive tape; contact with skin was facilitated by a thin application of thermally conducting grease (Eccotherm TC4). The bands were applied to the centre (vertically) of each of the ten regions listed in Table 1 except the head, where the band was attached just above the eyes. Their lengths were chosen so that they extended fully around each limb region and the head, and halfway around each trunk region from the anterior to posterior midline on the right hand side. The construction of bands, and their calibration by a method that allows for the local reduction of heat loss that they cause, have been described (Gin, Hayward & Keatinge, 1980). The electrical output from the bands was recorded by a Fenlow 501 digital voltmeter, input impedance 100 MΩ, and printer. An elastic net with a wide mesh (approximately 20 mm) was applied over the band on the head to prevent the band from slipping, since adhesion to hair on the head was less secure than adhesion to skin elsewhere on the body. Local tissue insulations, from body core to different skin areas, were calculated from measured heatflows and from the difference between rectal temperature and the temperature of the stirred water in the immersion tank. In calculating insulation for the head, allowance was made for the fact that in warm water immersions the spray to the head cooled due to evaporation, to approximately 1 °C below bath temperature.

Significances of differences between means were assessed by the t test, with pairing of data when appropriate. The t test was also used to assess significance of slopes or regression lines. Significances of differences between levels of regression lines were assessed by the F test (Snedecor & Cochran, 1967).

RESULTS

Whole body heat exchanges in cold water

Table 2 shows that on average the male subjects had smaller mean subcutaneous fat thicknesses than the female subjects. The men were also on average taller and heavier, and had larger surface areas and smaller surface area to weight ratios, than the women. When immersed in progressively colder water to the lowest water temperature at which each could stabilize body temperature, the women were generally found to be able to stabilize in colder water, and therefore to sustain a larger difference between deep body temperature and water temperature, than the men. There were, however, large individual differences within each group in the lowest water temperature at which stability was possible, one man being able to stabilize in water as cold as 12 °C while another could not do so in water below 32·2 °C. After body temperature had stabilized in the coldest water possible for that individual, exercise usually produced an initial small fall in temperature attributable to sudden return of cold blood from cold muscles, but a few minutes later deep body temperature began to rise or fall steadily. The Table shows that 15–30 min after starting exercise, body temperature was falling in three of the men, indicating that exercise had increased heat loss more than heat production and had therefore increased the water temperature in which these men could stabilize. In the other men, and in all of the women, exercise either had no effect on, or decreased, body temperature at this time. All subjects had difficulty maintaining the rate of work for the planned 30–45 min, and some failed to maintain it fully, indicating that the rate of work was at or near the maximum which they could sustain for long periods.

Figs. 1–3 show the degrees to which these differences between individual subjects, and between men and women, were associated with the thickness of their subcutaneous fat. Fig. 1*A* shows that when keeping still, subjects with a large thickness of subcutaneous fat could generally stabilize body temperature in colder water than subjects with less fat, but the scatter of results was large ($r = -0{\cdot}52$). The tendency of women to have thicker subcutaneous fat entirely accounted for their tendency to be able to stabilize in colder water than men; in fact, among people of given fat thickness there was a clear tendency for women to be slightly less well able than men to stabilize in the cold. Fig. 1*B* shows the lowest water temperature in which each subject could stabilize body temperature when exercising, calculated from metabolic rate and the rate of rise or fall in body temperature 15–30 min after starting exercise. Only thirteen points were obtained since one subject (F1) cooled below 35 °C when exercising, so that the immersion had to be ended soon after a steady rate of fall in temperature had been established and before the metabolic rate was measured. No individual value was very different from that found for the same subject at rest, and the relationship between lowest water temperature for stability and mean

TABLE 2. Heights, weights and mean fat thicknesses, maximum temperature difference which could be sustained between body and water temperature, and effect of exercise

Subjects	Mean subcutaneous fat thickness (mm)	Height (m)	Weight (kg)	Surface area (m^2)	Surface area/weight ($m^2 . kg^{-1}$)	Coldest water allowing stabilization of body temp.	Body temp. when stabilized in coldest possible water (°C)	Change in body temp. when exercising (°C . min^{-1})
M1	3·60	1·68	67·5	1·77	0·026	22·80	35·80	−0·035
2	4·05	1·87	72·0	1·96	0·027	19·00	35·60	−0·027
3	4·49	1·71	52·5	1·61	0·031	32·20	35·80	+0·020
4	4·54	1·68	74·5	1·84	0·025	22·00	36·40	+0·017
5	4·71	1·91	89·5	2·19	0·024	18·50	35·50	−0·023
6	5·73	1·79	77·0	1·96	0·025	12·00	36·30	0
7	5·78	1·80	75·5	1·95	0·026	19·00	35·55	+0·020
Mean (men)	4·70	1·78	72·6	1·90	0·026	20·79	35·85	−0·004
F1	5·16	1·67	57·5	1·64	0·029	22·00	35·20	—
2	5·17	1·74	67·1	1·81	0·027	20·00	35·25	0
3	5·24	1·72	57·5	1·68	0·029	20·00	35·25	0
4	5·36	1·65	50·5	1·54	0·030	24·00	36·15	+0·020
5	5·85	1·64	62·5	1·68	0·027	12·00	35·55	+0·027
6	6·12	1·77	65·0	1·81	0·028	23·00	35·75	+0·007
7	7·47	1·68	64·0	1·73	0·027	13·00	35·50	0
Mean (women)	5·77	1·70	60·6*	1·70*	0·028	19·14	35·52	+0·009

* Differs from mean for men $P < 0{\cdot}05$.

Male and female subjects are each numbered in order of increasing mean subcutaneous fat thickness.

subcutaneous fat thickness were much the same during exercise as at rest. There was, however, less scatter of results during exercise ($r = -0{\cdot}63$).

Fig. 2 (*A* and *B*) shows that total body insulation in the coldest water allowing stability was rather closely related to subcutaneous fat thickness, both at rest

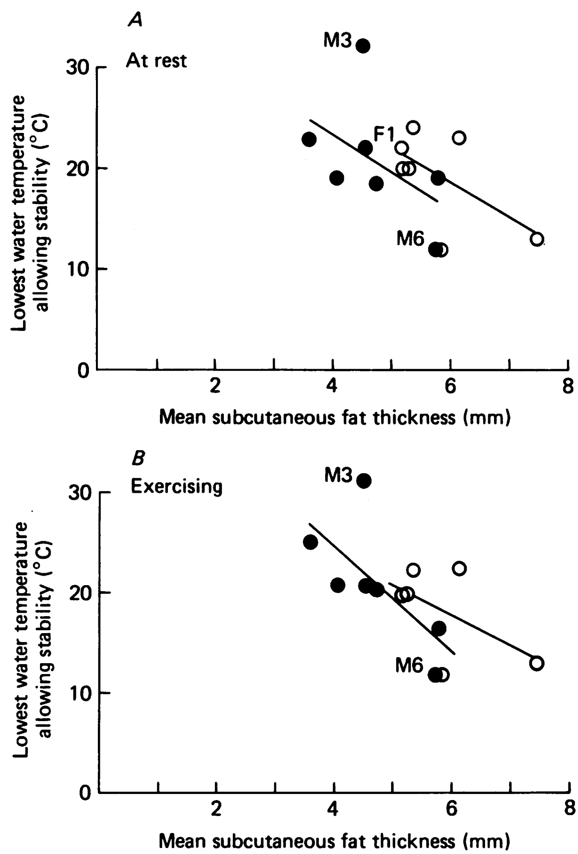

Fig. 1. Relationship between lowest water temperature at which body temperature could be stabilized, and mean subcutaneous fat thickness. *A*, at rest. *B*, exercising. ●, men; ○, women. Subjects can be identified from their fat thickness to compare with data in the tables, in which subjects are numbered in order of fat thickness. Subjects M3, M6 and F1 are labelled as each has a fat thickness close to that of another subject; no result was obtained for F1 exercising. Negative relationship between lowest water temperature for stability, and mean subcutaneous fat thickness, is significant ($P < 0{\cdot}05$) for all subjects during exercise. Values in *A* determined directly, in *B* calculated (see text).

($r = 0{\cdot}92$) and during exercise ($r = 0{\cdot}88$). Both the absolute values of the insulation, and the slope of its relationship to subcutaneous fat, were less during exercise than at rest.

Fig. 3*A* and *B* shows that the subjects' metabolic rates, in the coldest water allowing stability, varied greatly even among people of given fat thickness. These variations had little relationship to fat thickness although the metabolic rates tended to be rather higher in thin than fat people, both at rest and during exercise. Individual variations in metabolic rate were less with the subjects exercising than at rest in the cold water, but were still large compared to variations in total body insulation (Fig. 2) among people of comparable fat thickness. They were accordingly mainly responsible for the ability of some people to stabilize body temperature in water more

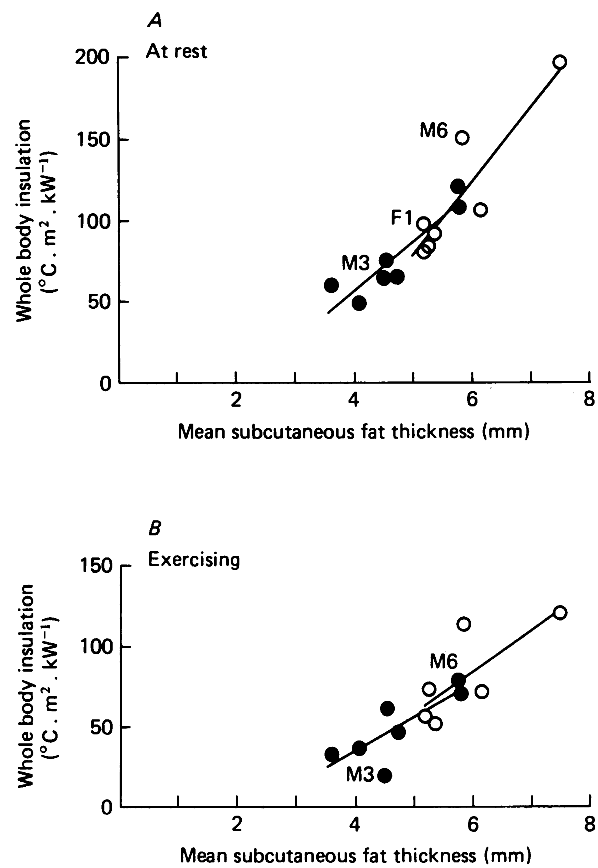

Fig. 2. Relationship between whole body insulation in coldest water allowing body temperature to stabilize, and mean subcutaneous fat thickness. *A*, at rest. *B*, exercising. Symbols as in Fig. 1. Relationship of insulation to mean subcutaneous fat thickness is significant ($P < 0{\cdot}05$) for men, for women, and for all subjects, at rest; also for men, and for all subjects, during exercise.

than 10 °C colder than was possible for other people with similar subcutaneous fat thickness (Fig. 1). However, comparison with Fig. 2 shows that among the fatter subjects, those with a high metabolic rate had a rather high insulation in relation to their fat thickness and vice versa. This is clearly seen with the four fattest women and the two fattest men, both at rest and when exercising. Among the thinner subjects, this association of a high metabolic rate with a high insulation in relation to fat thickness was not regularly present, probably because high muscle blood associated with marked shivering affected insulation more in thin people than fat, but it was present in one thin subject, M3, whose metabolic rate in the cold was exceptionally low, and whose insulation was also low. These results therefore imply that reactive people, who gave large metabolic responses to cold, generally also gave large cutaneous vasoconstrictor responses which contributed to their ability to stabilize in relatively cold water.

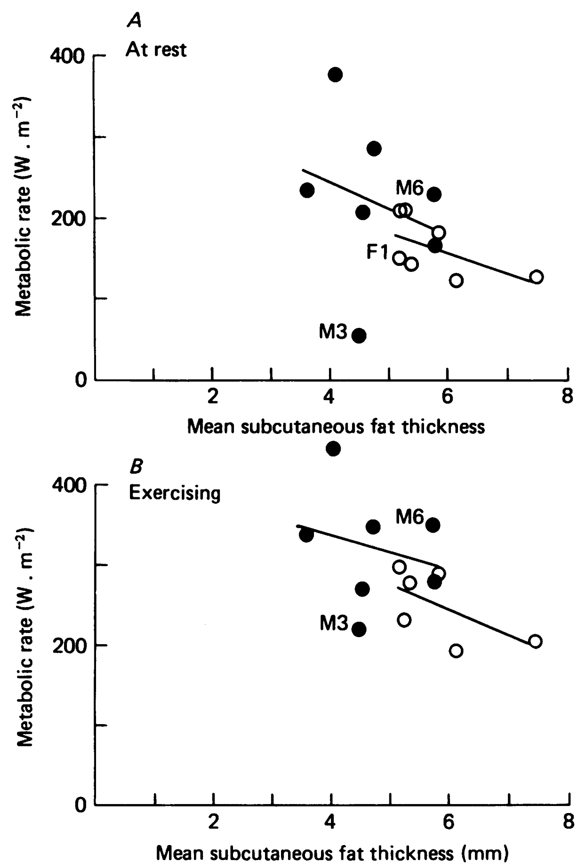

Fig. 3. Relationship between metabolic rate in coldest water allowing body temperature to stabilize, and mean subcutaneous fat thickness. *A*, at rest. *B*, exercising. Symbols as in Fig. 1. Negative relationship between metabolic rate and mean subcutaneous fat thickness is significant ($P < 0{\cdot}05$) for all subjects during exercise.

Comparison of Fig. 3*A* and 3*B* shows that the subjects in whom exercise produced relatively little increase in heat production were those who had already given the largest metabolic responses at rest (e.g. subjects M1, M2 and M5). Comparison with Table 2 shows that these three subjects were also the three in whom exercise increased heat production less than heat loss, causing body temperature to fall after it had stabilized at rest in cold water.

Regional fat thicknesses and insulations in cold water

Table 3 shows the regional surface areas of the subjects, and the subcutaneous fat thickness measured in each region. The readings include the thickness of the skin. The Table also shows the amount of insulation which could be provided by the measured thickness of skin and fat in each region, taking the insulating value of a 1 mm thick layer to be 4·88 °C . m^2 . kW^{-1} (Hatfield & Pugh, 1951). Thicknesses were greater in the trunk, thighs and calves than the head, arms, hands or feet, both in men and women. The thicknesses were greater in women than men in most regions, but particularly in the thighs and the upper and lower thirds of the trunk; in the thighs, fat thickness of women exceeded that of men by 52 %. The thighs were of particular importance in heat loss, as they represented the largest proportion of body surface of any region, 21 % in the men and 22 % in the women. The hands and feet were the only regions in which mean thicknesses were less in women than men, probably representing thinner skin on the palms and soles of women than men.

Table 4 shows the internal insulations of the different body regions after each subject's body temperature had stabilized in the coldest possible water. Each value of regional insulation in each subject was obtained by dividing the rate of heat flow measured near the midpoint of the region into the difference between deep body temperature and water temperature. These regional insulations were always greater than the amount of insulation available from the measured thickness of skin and subcutaneous fat at the same site, given in Table 3. The difference was least in the upper and middle parts of the trunk where over half the insulation with the subjects at rest could be accounted for by skin and fat, and greatest in the hands and feet where insulation was much higher, and where less than 3 % of it could be accounted for by skin and fat. Muscular parts of the limbs were intermediate, rather less than a third of their actual insulation being attributable to skin and fat in the thighs and less than a quarter in the calves, upper arms and forearms. The Table shows that exercise caused the insulations measured at the midpoints of the thighs, calves, upper arms and forearms to decrease, but had no clear effect on those measured for the trunk or for the hands and feet. Water colder than 20 °C on the head caused headache which prevented continuous cooling of the head, and therefore measurement of the insulation of the head, in the four subjects able to stabilize in water colder than 20 °C. The insulations measured on the heads of the other ten subjects, which include insulation provided by hair, were similar to those of the trunk, indicating that internal insulation deep to the skin surface was rather lower in the head than in the trunk; this is in keeping with the finding by Wade *et al.* (1979) of a higher heat flux from the forehead than the trunk of people in water at 25 °C.

These internal insulations measured near the centre of each region differed from the effective mean insulation of each region. When at rest in cold water the subjects tended to hunch up and to draw their limbs towards the midline. This was checked at the experimenters' request and no region covered by a heatflow band was in contact with another skin surface, but it remained sufficient in most cases to occlude areas of skin in regions such as the axillae, groins and flexor surfaces of the neck and limb joints. This is reflected in a discrepancy between total body heat loss and local rates of loss measured on exposed skin in the cold. When the subjects had stabilized body

TABLE 3. Regional surface areas and fat thickness

	Head	Upper trunk	Mid trunk	Lower trunk	Thighs	Calves	Feet	Upper arms	Lower arms	Hands
	Surface area, both halves of body (m^2)									
Men	0·126 ±0·004	0·214 ±0·012	0·214 +0·012	0·214 ±0·012	0·392 ±0·019	0·222 ±0·009	0·129 ±0·007	0·177 ±0·008	0·109 ±0·002	0·100 ±0·004
Women	0·112 ±0·002	0·188 +0·004	0·188 ±0·004	0·188 ±0·004	0·378 ±0·013	0·207 ±0·008	0·109 ±0·003	0·152 ±0·005	0·099 ±0·011	0·077 ±0·004
	Subcutaneous fat thickness (mm)									
Men	3·38 ±0·49	4·60 ±0·77	4·58 ±0·90	5·93 ±2·07	5·02 ±1·21	5·21 ±1·08	3·89 ±0·57	4·37 ±0·54	3·88 ±0·47	3·86 ±0·64
Women	3·51 ±0·37	6·84 ±1·24	4·89 ±1·18	7·29 ±2·02	7·65 ±1·01	5·67 ±0·79	3·48 ±0·42	4·48 ±0·88	4·14 ±0·57	3·47 ±0·53
	Insulation of this fat when not perfused with blood (°C . m^2 . kW^{-1})									
Men	16	22	22	29	24	25	19	21	19	19
Women	17	33	24	36	37	28	17	22	20	17

Values are means (±S.E.), seven subjects.

TABLE 4. Local internal insulations measured near midpoint of each region in coldest water allowing stability (°C . m^2 . kW^{-1})

	Head	Upper trunk	Mid trunk	Lowertrunk	Thighs	Calves	Feet	Upper arms	Lower arms	Hands
	At rest									
Men	45±8	39±5	34±3	53±9	86±11	138±14	990±463	87±17	103±14	926±215
Women	50±6	48±7	45±7	85±18	122±13	178±12	1592±257	95±14	128±17	3239±685
	Exercising									
Men	50±11	37±6	35±5	51±10	69±11	88±18	933±360	64±11	74±14	1284±316
Women	41±3	49±8	48±9	86±18	103±12	110±13	3297±1317	74±10	85±16	3722±1299

Values are means (±S.E.) for seven subjects, except those for the head which are for five subjects (see text). They represent measured differences between deep body temperature and water temperature, divided by measured local heat flow, and so include all sources of internal insulation including countercurrent heat exchange.

temperature at rest in the coldest water allowing stability, total heat loss, obtained as metabolic heat production minus respiratory heat loss, averaged 394 W in the male subjects. This was only 0·85 of their mean over-all heat loss (464 W) indicated by multiplying the surface area of each region by the heat loss measured near the centre

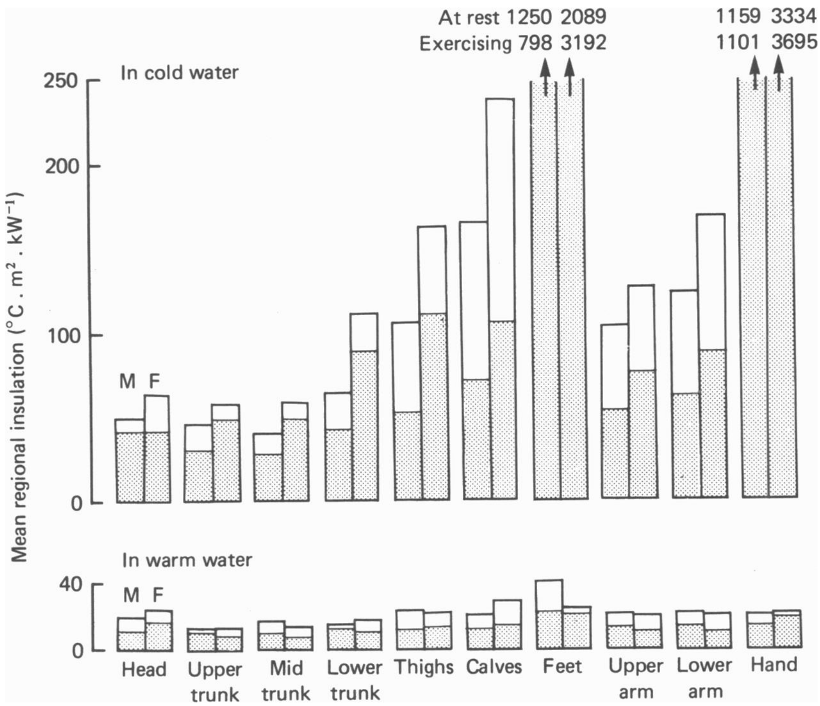

Fig. 4. Mean regional insulations after stabilization of body temperature in (top) coldest water allowing stabilization, (bottom) warm water 37 ± 0·5 °C. Values are effective mean insulations for the whole of each region per unit area, including occluded skin (see text).

Exercising { } At rest

Left hand column of each pair is average of values for men, right is average for women.

$n = 7$ except for readings for the head in cold water, and for all regions of men exercising in warm water, where $n = 5$ (see text).

of the region. In the women, total heat loss obtained as metabolic heat production minus respiratory heat loss was 251 W, only 0·74 of the mean over-all heat loss (338 W) indicated by multiplying the surface area of each region by the heat loss measured near the centre of it. During exercise very little of the skin surface was protected, and overall loss obtained as metabolic heat production minus respiratory heat loss, with allowance when necessary for loss or gain of stored heat, was close to and often greater than that obtained by multiplying local surface areas by heat losses measured near the centre of them. In men exercising, total heat loss averaged 590 W, 1·17 of that indicated by multiplying the regional areas by heat losses measured near their centres (504 W). In women exercising (subjects F2–7 inclusive), total heat loss averaged 360 W, 0·97 of that obtained by multiplying regional areas by heat losses measured near their centres (372 W). Such factors, obtained in each subject in each experiment, were used to adjust locally measured heat losses to give the effective mean insulations of the various regions. The adjustment, which assumes the factor to be similar in all regions of the body in a given subject, corrects for any difference of the measured insulation in each region from mean insulation over all

TABLE 5. Heat exchanges during heat balance at rest and exercising in warm water (37 ± 0·5 °C)

	Body temperature (°C) above water		Whole body insulation (°C . m². kW⁻¹)		Metabolic rate (W . m⁻²)	
Subjects	At rest	Exercising	At rest	Exercising	At rest	Exercising
M1	1·10	2·00	21·0	9·3	52·4	216
M2	0·73	1·27	12·0	5·5	60·8	230
M3	0·67	1·80	10·7	7·1	62·9	253
M4	1·05	2·05	20·5	10·6	51·2	194
M5	0·75	1·90	10·4	8·8	71·9	216
M6	1·00	2·20	19·6	10·6	50·9	208
M7	1·25	2·20	24·6	14·5	50·8	152
Mean (men)	0·94	1·92*	17·0	9·5*	57·3	210*
F1	0·70	1·60	14·2	7·6	49·3	210
F2	0·85	1·95	12·6	9·4	67·3	207
F3	0·75	1·40	13·9	10·1	54·0	138
F4	0·85	1·30	16·6	8·3	51·2	156
F5	0·70	1·35	15·6	13·5	44·9	100
F6	0·75	1·40	16·0	9·3	47·0	151
F7	0·80	1·25	20·9	15·2	38·3	82
Mean (women)	0·77	1·46*†	15·7	10·5*	50·3	149*†

* Differs from mean at rest $P < 0.05$.
† Differs from mean for men $P < 0.05$.

of the region, as well as for protection or occlusion of part of its skin surface. Fig. 4 (top) shows that these mean regional insulations, in all regions except the women's hands and feet, were lower during exercise than at rest. Since muscular parts of the limbs were the only regions in which measured internal insulation of exposed areas fell appreciably during exercise (Table 4), most of the decreases in mean regional insulations which took place with exercise were attributable to exposure during exercise of cutaneous areas which were protected at rest.

Whole body heat exchanges in warm water

Table 5 shows that when the subjects were at rest in warm water (37 ± 0·5 °C) they stabilized their deep body temperatures at only 0·67–1·25 °C above that of the water. Their whole body insulations at this time were much lower and more uniform that they had been in cold water. The Table also shows that exercise in the warm water caused some further decrease in whole body insulation, but a proportionately larger

TABLE 6. Local internal insulations in °C . m^2 . W^{-1} measured near midpoint of each region in warm water (37 ± 0·5 °C)

	Head	Upper trunk	Mid trunk	Lower trunk	Thighs	Calves	Feet	Upper arms	Lower arms	Hands
					At rest					
M	19·8	15·2	21·6	18·1	25·5	22·1	36·4	21·2	21·6	20·8
	± 4·0	± 3·2	± 5·2	± 4·2	± 5·0	± 3·9	± 9·3	± 2·0	± 3·7	± 5·0
F	24·1	14·9	15·3	19·1	23·9	31·4	26·7	21·9	20·2	22·2
	± 6·8	± 2·3	± 3·0	± 3·4	± 2·3	± 2·9	± 3·3	± 1·9	± 1·4	± 3·9
					Exercising					
M	15·8	14·2	14·8	18·2	17·9	17·8	31·7	18·5	19·3	19·9
	± 3·8	± 3·0	± 3·6	± 3·4	± 2·1	± 1·9	± 2·6	± 2·1	± 3·2	± 3·6
F	23·2	13·8	14·3	18·6	24·1	24·7	35·4	16·8	16·9	29·1
	± 4·8	± 1·0	± 2·3	± 3·6	± 4·7	± 1·7	± 4·2	± 2·4	± 2·4	± 3·9

Values for the head include insulation provided by hair.

All values are means (± S.E.) for seven subjects, except those for men exercising which are for five subjects; values for subjects M2 and M5, in which some readings were lost during exercise, are omitted.

increase in metabolic heat production, so that body temperatures rose to 1·25–2·20 °C above water temperature. Whole body insulation was usually lower in fat than thin people; the slope of the regression of insulation on mean fat thickness was significant ($P < 0{\cdot}01$) during exercise, when the scatter of the results was lower than at rest. However, the fatter subjects had lower metabolic rates per unit surface area than the thinner subjects in the warm water, both at rest ($P < 0{\cdot}05$) and during exercise ($P < 0{\cdot}01$). This generally outweighed the difference in insulation, so that the fatter people tended to stabilize with smaller differences in temperature between body core and water than the thinner ones, particularly during exercise. Equations for these regressions are given in the Appendix. Women, with greater mean fat thickness in most cases, usually had lower metabolic rates than men, both at rest and during exercise, and accordingly stabilized their body temperatures closer to water temperature than the men. All subjects felt uncomfortably hot, and found it difficult to maintain the planned rate of work, during the 30–60 min required to stabilize body temperature in warm water.

Regional insulations in warm water

Table 6 shows that regional tissue insulations measured in the warm water were lower, and were much more uniform between different parts of the body, than they had been in cold water. There was still some tendency to higher insulation in the limbs, particularly the feet, than in the upper part of the trunk. Insulations for the head in warm water, which include insulation of hair, were usually rather higher than those of the trunk.

When at rest in warm water the subjects kept their limbs spread out so that skin surfaces were well exposed. Body heat losses calculated from measured values near the centre of each region and regional surface areas (116 W on average in men, 82 W in women) accordingly matched quite closely heat losses calculated from metabolic rate (109 W on average in men, 85 W in women). Mean insulations of each region, calculated as before to allow for such discrepancies (Fig. 4), were therefore little different from the insulations measured near the midpoint of each region.

During exercise in warm water, regional heat losses were under-recorded because profuse sweating and movement caused heatflow bands to detach partially at the edges. Body heat losses calculated from regional readings during exercise in the warm and from regional surface areas (273 W on average in the men, 150 W in women) were accordingly lower than those calculated from metabolic rate (370 W on average in men, 253 W in women). The mean regional insulations given in Fig. 4 allow for such discrepancies as well as for any other cause of difference between locally measured and mean regional insulations in each subject. They indicate rather lower mean regional insulations for all parts of the body during exercise than rest in warm water.

DISCUSSION

The most notable general finding about people's ability to stabilize body temperature in cold water was that although it depended greatly on the internal insulations achieved, which in turn were closely related to their subcutaneous fat thicknesses. it also depended to about the same degree on the size of their metabolic responses to cold and to a smaller degree on associated differences in vasoconstrictor response. These differences in metabolic rate, at the time that each person stabilized body temperature in the coldest water in which he or she could do so, were much larger than individual variations in metabolic rate recorded in people of given fat thickness when immersed for uniform periods of 30 min in water at a uniform temperature of 15 °C (e.g. Keatinge, 1960). This can be explained by the fact that someone giving a large metabolic response when immersed in progressively colder water, and enabled by it to stabilize in relatively cold water, will thereby be exposed to more intense stimulation of cutaneous receptors. This will amplify any tendency of given people to give large metabolic and vasoconstrictor responses to cold, so that moderate differences in people's responsiveness to a given cold stimulus result in larger differences in the water temperature in which they can maintain thermal stability. The underlying tendency of some of our subjects to react more or less to cold than others can be largely explained by known factors. Subject M3, who gave unusually small metabolic and vasoconstrictor responses and could not stabilize in water colder than 32 °C, had undergone repeated recent exposures to cold air. Repeated exposure to cold, both in the field (e.g. Carlson, Burns, Holmes & Webb, 1953; Keatinge & Evans, 1958; Nelms & Soper, 1962; Hanna & Hong, 1972; Rochelle & Horvath, 1978; Golden, Hampton & Smith, 1979), and in the laboratory (Glaser & Whittow, 1957; Keatinge, 1959, 1961*a*), usually reduces subsequent metabolic and vasoconstrictor responses to cold. The mass of muscle available for shivering is another obvious factor affecting the metabolic response. People with a high ratio of surface area to total mass will tend to have a low muscle mass in relation to surface area; comparison of Table 2 with Fig. 3*A* shows that such people (e.g. F4) usually did produce less heat than other people per unit surface area in the cold water. The tendency of physical training to increase muscle mass and work capacity is well known, and subject M2, who was in the highest state of physical training, had the highest metabolic rate in the cold; his surface area to mass ratio was close to the average for the group.

The differences in heat exchange which we saw between men and women were all attributable, within the limits of experimental error, to differences in fat thickness and in surface area to mass ratio. The known tendency of women to have thicker subcutaneous fat than men, particularly over the thighs and abdomen (Edwards, 1951; Sloan & Keatinge, 1973), fully accounted for their greater insulation when stabilizing in cold water in the present study. The tendency of our female subjects to be shorter than the men and so to have a higher surface area to mass ratio (see Kollias, Barlett, Bergsteinova, Skinner, Buskirk & Nicolas, 1974), can account for their tendency to have lower metabolic rates in the cold, and accordingly to be able to stabilize in rather less cold water, than men of the same fat thickness.

The present measurements of regional heat loss and fat thickness confirm earlier evidence (e.g. Cannon & Keatinge, 1960; Wade *et al.* 1979) that most of the loss of body heat in cold water takes place through the skin of the trunk. They also showed that skin and subcutaneous fat could account for most of the internal insulation of the trunk. Although less than half the insulation of muscular parts of the limbs and very little of the high insulation of the hands and feet in the cold were due to fat, the large role of fat in providing regional insulation of the trunk, which was the main source of heat loss in the cold, explains the close relationship of overall body insulation in the cold to mean subcutaneous fat thickness.

A surprising finding was that once body temperature had stabilized in cold water, the internal insulation of the trunk was not significantly affected by exercise. This contrasts with two studies using thermography which indicated much higher temperatures over the upper trunk, suggesting lower internal insulation there, after swimming than after still immersions in cold water (Hayward, Collis & Eckerson, 1973; Wade & Veghte, 1977). One reason may be that the immersions in those experiments were brief (15 and 5 min respectively) so that shivering is likely to have been slight, and bloodflow low and insulation high, in muscles of the upper trunk when the subjects were at rest; exercise could then increase muscle bloodflow and substantially reduce insulation provided by muscle. When our subjects stabilized body temperature at rest in cold water they were usually shivering considerably, and during prolonged exposures to cold shivering is known to take place largely in trunk rather than limb muscles (Golenhofen, 1965). Blood flow in muscles of the trunk is therefore likely to have been high even when our subjects were at rest in cold water, leaving little scope for exercise to decrease the insulation they provided. The lesser involvement of limb than trunk muscles in shivering can explain why exercise in cold water did increase insulation in the limbs in our subjects, but this decrease in limb insulation was not very large. The present results in fact show that the large decreases in total body insulation which exercise in cold water produced in these studies, as in earlier ones (Keatinge, 1961*b*; Nadel, Holmer, Bergh, Astrand & Stolwijk, 1974) were due in large part to exercise exposing skin areas protected by the hunched-up posture involuntarily adopted at rest in the cold.

The additional heat loss which exercise produces, by either decreasing internal insulation or exposing protected skin, must, from first principles, be greater in cold than in relatively warm water. Earlier studies showed that exercise almost always increases heat loss more than heat production when people are immersed in water too cold to allow them to stabilize body temperature at rest (Cannon & Keatinge, 1960; Hayward, Eckerson & Collis, 1975), but that it increases heat loss less than heat production in warmer water at 35 °C (Keatinge, 1961*b*). The present experiments show that in water at a temperature at which people could just maintain body temperature when still, the effect of exercise depended on how much the individual had reacted to cold when at rest. The main point of practical interest is that exercise could then increase body temperature in people who had allowed their temperature to drift down to near 35 °C, with little metabolic response, when they were at rest in relatively warm water, although it caused progressive body cooling in people who had been enabled to stabilize body temperature by a large metabolic response to cold.

The well-known vasodilatation which takes place in the skin in warm conditions (e.g. Roddie, Shepherd & Whelan, 1956) can account for insulation being not only lower but also much more uniform betwen different subjects and different skin areas when the subjects were in warm water than cold. Nevertheless, this uniformity in the warm was not total. The most notable departure from it was the fact that insulation remained appreciably higher in fat than thin subjects, even during exercise when deep body temperatures were raised to well over 38 °C and thermal vasodilatation is likely to have been maximal. A non-significant tendency to higher insulations in fat than thin people in warm water was observed previously (Cannon & Keatinge, 1960). The finding implies that physical conduction of heat through the skin and fat was significant, in relation to transport of heat through it by bloodflow, even during cutaneous vasodilatation. The other departure from uniformity in our subjects in the warm, a tendency for insulation to be higher in the limbs than the trunk, may be due in part to countercurrent exchange of heat (Bazett, Love, Newton, Eisenberg, Day & Forster, 1948) continuing to limit heat loss from the limbs appreciably even during vasodilatation. Our finding that the insulation of the head was higher in the cold than the heat, but to a smaller degree than that of any other part of the body, confirms the findings of Froese & Burton (1957) who used a calorimeter to show that insulation of the head was only slightly higher in cold than warm air.

A number of models have been devised to predict people's ability to withstand exposure to cold. Most are based on assumptions of specific relationships between peripheral blood flows and metabolic heat production on one hand, and surface and deep body temperatures on the other (e.g. Bullard & Rapp, 1970; Wissler, 1971; Hardy, 1972; Hwang & Konz, 1977; Baker, Harnett & Ringuest, 1979). Most assume insulation between body core and environment, during cutaneous vasoconstriction in the cold, to be either that provided by blood-free skin, or by blood-free skin and subcutaneous fat together; the last authors found large discrepancies between actual body cooling in volunteers and that predicted from such models. The most important prediction usually needed is whether given people will be able to stabilize body temperature in water at a given temperature. Our data allow this prediction to be made directly (Fig. 1) for unprotected people of given mean subcutaneous fat thickness, both at rest and during near-maximal exercise. They show that in individual cases variations in metabolic response cause substantial departures from the most probable value, but that these in turn can be predicted to some degree if the individual's state of acclimatization and physical fitness are known, and if surface area to mass ratio is evaluated from height and weight. A similar prediction can be made from our data for people with given patterns and amounts of external insulation, but in this case requires details of local insulation in each body region for people of given mean fat thickness during exposure to maximum sustainable cold stress. The Appendix gives these relationships for our subjects in cold water, and some additional data from warm immersions which facilitate similar calculations for people in hot conditions. It also gives relationships between mean subcutaneous fat thickness and readings made by either ultrasound or calipers at specified sites, which allow mean thickness to be determined conveniently from a small number of readings.

APPENDIX

Calculation of differences in temperature sustainable between body core and hot or cold environments, with given external insulations

From first principles, the minimum external temperature in which body temperature can be stabilized with given patterns of external insulation, in °C below body core temperature, is obtained by multiplying M (metabolic rate minus respiratory heat loss, per unit surface area, in $\mathrm{W\,.\,m^{-2}}$), by the reciprocal of I_t (I_t is total body insulation in $\mathrm{°C\,.\,m^2\,.\,W^{-1}}$). I_t represents $\Sigma[A/(I_r+I_e)]$ for all regions of the body; where A is the surface area of each body as a fraction of total body surface; I_r and I_e are respectively mean internal insulation of each body region, and the external insulation applied to it, in $\mathrm{°C\,.\,m^2\,.\,W^{-1}}$.

Mean subcutaneous fat thickness. Mean subcutaneous fat thickness of the entire body in mm (F), needed to predict I_r, was itself closely predictable in our subjects from measurements of ultrasonic fat thickness made at only four of the sites used. Values for F given in Table 2 were related to the sum of fat thicknesses in mm (S_u) measured ultrasonically at the following sites: (*a*) front of middle of upper arm, (*b*) anterolateral point of middle third of trunk, (*c*) 20 mm to the side of the midline, middle of lower third of trunk, (*d*) anterior mid line of the middle of the thigh; by the equations

In men, $$F = 1{\cdot}308+0{\cdot}181S_u (r = 0{\cdot}97, \text{ slope } P < 0{\cdot}001, n = 7).$$

In women, $$F = 1{\cdot}933+0{\cdot}168S_u (r = 0{\cdot}99, \text{ slope } P < 0{\cdot}001, n = 7).$$

Mean subcutaneous fat thickness was also predictable, with less accuracy, from the sum of four readings of skinfold thickness in mm (S_c) made on our subjects by Harpenden calipers at: (*a*) lower corner of scapula, (*b*) lower margin of ribs in midclavicular line, (*c*) 50 mm below and lateral to umbilicus, (*d*) at the midpoint of the front of the upper arm; by the equations

In men, $$F = 3{\cdot}091+0{\cdot}0357S_c (r = 0{\cdot}83, \text{ slope } P < 0{\cdot}05, n = 7).$$

In women, $$F = 4{\cdot}093+0{\cdot}0359S_c (r = 0{\cdot}83, \text{ slope } P < 0{\cdot}05, n = 7).$$

Insulations and sustainable temperature differences between body core and surroundings in cold water. Values of I_r for each body region during maximum sustainable cold stress can be obtained from the subject's mean subcutaneous fat thickness by the regression equations given in Table 7. These give the relationship of I_r for each region to F in our subjects at the time body temperature had stabilized in the coldest possible water. They are calculated from pooled data from all male and female subjects, since the regressions for men and women did not differ significantly in any region.

The surface area of each body region, as a fraction of total surface area (A) can be obtained by dividing the mean regional areas given in Table 3 by mean overall surface area (1·90 m^2 for men, 1·70 m^2 for women). I_t can then be obtained as the reciprocal of $\Sigma[A/(I_r+I_e)]$ for all regions of the body, and multiplied by M to give the minimum water temperature in which deep body temperature can be stabilized in °C below body temperature.

The most probable value of M at rest and during near-maximal sustained exercise in cold water, can be obtained from the regression of M with respect to F for our subjects when they had stabilized in the coldest possible water:

At rest, $$M = 361-35{\cdot}5F \quad (r = -0{\cdot}34, n = 14).$$

Exercising, $$M = 470-39{\cdot}8F \quad (r = -0{\cdot}45, n = 13).$$

The low values of r indicate that departures from the most probable values of M, calculated in this way, are large in individual cases. Lower values of M than the regressions predict can be anticipated in people known to have had extensive prior exposures to cold, and higher values in people who are warm acclimatized but in a high state of physical training or have high surface area to mass ratios; the lowest values of M in any of our subjects were 56 W . m^{-2} at rest (subject M3) and 179 W . m^2 exercising (subject F6); the highest values were 342 W . m^{-2} at rest and 402 W . m^{-2}

TABLE 7. Relationships between mean regional insulations in cold water and overall fat thickness of the individual

Head	Upper trunk	Mid trunk	Lower trunk	Thighs	Calves	Feet	Upper arms	Lower arms	Hands
					At rest				
(57·5)	−57·8* +21·1F	−48·5* +18·9F	−204·4* +56·4F	−137·2* +51·9F	−11·7* +40·7F	(1669·6)	−21·6 +26·1F	−3·2 +28·4F	(2246·6)
					Exercising				
(42·7)	−41·1* +15·6F	−43·7* +15·7F	−129·9* +37·4F	−96·9* +34·3F	−18·3* +20·4F	(1995·2)	−4·6 +11·8F	−20·0 +10·6F	(2397·9)

These are the regression equations for the mean insulation of each region in °C . m^2 . kW^{-1}, (multiply by 10^{-3} for insulations in °C . m^2 . W^{-1}) against the individual's mean subcutaneous fat thickness (F) in mm; for $F > 4$ mm. In regions where local fat thickness was small and virtually invariant, only average values for the whole group are given (in brackets).

Values are derived from pooled data from seven men and seven women, except those for the head (five men and five women).

* Slope significant $P < 0·05$; correlation coefficient $> 0·59$.

exercising (subject M2). These values are a little lower than metabolic rates given in Fig. 3 because of the allowance made in them for respiratory heat loss.

Insulations and sustainable temperature differences between body core and surroundings in warm water

The maximum external temperature in which deep body temperature can be stabilized in a warm environment with given patterns of external insulation, in °C below body temperature, can be calculated more simply, since regional differences in heat loss in the warm were small enough to be ignored without serious error. I_r for all body regions can be taken from the data in Table 5 as $16{\cdot}4 \times 10^{-3}$ °C . m^2 . W^{-1}, the mean value found at rest which was not greatly affected by fat thickness, and as $(-0{\cdot}71 + 2{\cdot}04F) \times 10^{-3}$ °C . m^2 . W^{-1} ($r = 0{\cdot}71$) in exercise. M can be taken from the data in Table 5 as $(84 - 5{\cdot}82F) \times 10^{-3}$ °C . m^2 . W^{-1} ($r = -0{\cdot}62$) at rest, and $(397 - 41{\cdot}6F) \times 10^{-3}$ °C . m^2 . W^{-1} ($r = -0{\cdot}80$) during near-maximal exercise by untrained people in the heat.

Applicability of the calculations

The only major limitation to these predictions for people in water is that they will not apply if any extensive part of the body surface cools below 12 °C, causing cold vasodilatation and high local heat loss. They can be applied to people in air, provided that the effective insulation of the air associated with existing wind speed is known and is added to the external insulation, and, in warm air, when sweat is prevented from evaporating by saturated air or by impermeable clothing. Some error may be expected if skin temperatures are grossly uneven or fluctuate greatly.

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