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THE METABOLIC RATE AND HEAT LOSS OF FAT AND THIN MEN IN HEAT BALANCE IN COLD AND WARM WATER

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Shivering can be produced by the return of cold blood from the limbs (Sherrington, 1923–4; Uprus, Gaylor & Carmichael, 1935; Glaser & Holmes-Jones, 1951) but observations that it can be produced by surface cooling alone (Jung, Doupe & Carmichael, 1937; Davis & Mayer, 1955; Good & Sellers, 1957; Spurr, Hutt & Horvath, 1957) suggested that deep cooling might be of little importance in practice. However, it has been reported (Keatinge, 1960*a*) that although the rate at which men's rectal temperatures fell in water at 15° C was closely related to their subcutaneous-fat thickness, their early metabolic response to the cold immersion was not, and the metabolic rates of thin men only rose substantially above those of the fat men during the later part of immersions, when the thin men's rectal temperatures fell. The present studies of fat and thin men in a steady state of heat exchange in water were designed partly to confirm or refute this evidence that stimulation of deep temperature receptors plays a major part in adjusting the metabolic rates of fat and thin men to their different rates of heat loss during prolonged exposures to cold. They were also designed to show whether fat and thin men have different critical ambient temperatures, at which physical temperature regulation is complete and below which the metabolic rate is increased (Rubner, 1902; Burton & Bazett, 1936; Scholander, Hock, Walters, Johnson & Irving, 1950).

It was hoped that these experiments would also show whether cold vasodilatation substantially reduced the tissue insulation of fat men in near-freezing water. This seemed probable, as cold vasodilatation takes place eventually in cold extremities of even generally chilled people (Keatinge, 1957) and appears to be due largely to the direct effect of low temperatures on blood vessels (Keatinge, 1958). Physical exertion accelerates the fall in the rectal temperature of thin men in water at 16° C (Pugh & Edholm, 1955) and in water at 5 and 15° but not at 25 or 35° C (Keatinge, 1959) and shivering may cause a fall in the total body insulation (Burton & Bazett, 1936; Carlson, Hsieh, Fullington & Elsner, 1958). It was hoped that the present experiments would provide information about the effect of shivering on the tissue insulation of fat and thin men, and additional experiments were made to determine whether work assisted the maintenance of the body temperature of either fat or thin men in water just too cold for them to maintain thermal stability when still, since this question is of practical importance.

A preliminary communication (Keatinge, 1960*b*) of some of these and of some earlier results has been made already.

METHODS

The subjects were eight healthy naval ratings aged between 17 and 21, none of whom had recently been exposed to an unusual degree of cold. They were volunteers and were selected to include both fat and thin men. On arrival each was given a medical examination, his height and weight was determined, and his skin-fold thicknesses measured with Harpenden callipers at four sites (Keatinge, 1959). Each man was repeatedly immersed over a period of one week in water at temperatures ranging from 38° C down. The food intake was not restricted before immersions. The immersions at 38, 36 and 34° C, which were made first, were 'crossed over' as far as possible, but those at lower temperatures were not. Six of the eight men were immersed in water at 38° C until their temperatures had become stabilized, but the other two subjects, 3 and 7, became so uncomfortable that they had to be allowed out before this, so that no values for insulation of these two men at this temperature could be calculated. Subjects 2 and 3 were unwilling to go into water colder than 28° C but the six others were all immersed at progressively lower temperatures, until a water temperature was found at which their temperatures were still falling steadily after 2½ hr in the water, or at an accelerating rate at the end of somewhat shorter immersions. Five of these men were immersed again at this last temperature and were told to work as hard as possible on this occasion. The experiments were made during October, November and December.

The immersions were performed in an indoor tank, 8 × 4 × 4 ft. (3·6 m^3). The subject sat in the tank on a slatted wooden seat wearing only a pair of very brief bathing trunks and a large fleece-lined helmet which covered much of the face and the whole of the rest of the head. The water just covered his shoulders and was vigorously stirred by a mechanical device; the temperature of the immersed skin has been shown to be within about 1° C of water temperature under these conditions, even in water as cold as 5° C, within 20 min after immersion (Keatinge, 1959). The water was maintained within 0·1° C of the required temperature by electrical heating or refrigeration, and the room temperature was maintained by electrical heating at 25 ± 1° C. In the few 'working' experiments the work consisted of a rowing movement, with the subject on a sliding seat in the water and with his feet attached to the end wall of the tank. This tank and accessory apparatus has been described in detail (Keatinge, 1959).

Rectal temperature was measured by a thermojunction enclosed in semi-rigid plastic tubing inserted 11 cm from the anus. The cold junction was in a vacuum flask of ice and water, and the e.m.f. was measured by a potentiometer. Readings were accurate to the nearest 0·05° C. Stability of the rectal temperature was defined arbitrarily as the absence of a change greater than 0·1° C during any period of 30 min starting at least 30 min after the man was immersed. A change of 0·05° C or less in 15 min was, however, accepted in some immersions at the lowest temperatures, if the subject was very anxious to leave the water. The collection of expired air for determination of the metabolic rate was restarted repeatedly until the rectal temperature was found to have been 'stable' throughout the period of collection.

During metabolic-rate determinations the subject was fitted with a mouth-piece and nose-clip. The men wore these for 10–20 min before the first immersion, to get used to them. The inspired air was led to the subject from outside the building through a copper duct which warmed it to room temperature. The expired air was led from the subject through a Max-Planck Institute Respirometer which measured its volume, and the oxygen deficit of the gas was analysed by an automatic analyser (Hartmann und Braun, Frankfurt-am-Main). The metabolic rate was then calculated by the method of Weir (1949) from the volume of expired air corrected to s.t.p. and its oxygen deficit.

Tissue insulation is expressed as the reciprocal of the kilocalories dissipated per square meter of immersed skin per degree centigrade temperature gradient between the rectum and the water. This was generally calculated when the men were in a steady state of heat exchange, assuming the rate of heat loss to be the metabolic rate minus the heat loss due to evaporation and warming of the inspired air from room temperature to body temperature. This air was drawn from outside the room. The outside day temperature was always between 0 and 10° C and the humidity 85–100 % during the period of the experiments. The air was found to be warmed to 25 ± 1° C when inspired. In calculating the respiratory heat loss, the air was assumed to be 90 % saturated with water vapour at 5° C when drawn from outside, to be at 25° C when inspired by the subject and to be almost saturated with water vapour at 37° C when expired (Christie & Loumis, 1932). The errors introduced into the calculated body insulation by making these assumptions are unlikely to have exceeded ± 2 %. The total surface area of the men was obtained from their height and weight by the nomogram of Hawk, Oser & Summerson (1947). Since the head represents approximately 6·6 % of the surface area of men (Sawyer, Stone & Dubois, 1916) the area of the men's skin immersed in the water was taken as 93·4 % of the total skin area. Heat loss from the head, which was covered by a fleece-lined helmet, was assumed to be negligible. In a few experiments at low temperatures, in which the men's temperatures failed to become stabilized, approximate values for tissue insulation were calculated. In calculating these allowance was made for the loss of stored heat from the deep tissues of the body, assuming these to represent 64 % of the total mass of the body and to have a specific heat of 0·83 (Burton, 1935), and their fall in temperature to be that measured in the rectum.

In many experiments heat-flow disks (Hatfield, 1949) were stuck by 'Nobecutane' (Evans) to the dorsum of the terminal phalanx of the right index finger, the middle of the flexor surface of the forearm, the skin over the sternum at the level of the 4th intercostal space, the abdomen just above the umbilicus, and the dorsum of the right foot. Since difficulty was experienced in making the disks stick securely for long periods they were supported by loose rubber bands round their bases in the first two positions, and in the others were held on by the tips of wooden pointers while readings were taken.

RESULTS

Table 1 gives the skin-fold thickness of the subjects together with their heights and weights, total surface areas and the surface areas immersed during the experiments. The subjects are numbered in the order of their skin-fold thicknesses. The first four had similar mean skin-fold thicknesses, between 6·5 and 8·5 mm, while subjects 7 and 8 who appeared obese had mean skin-fold thicknesses of 26·7 and 26·8 mm.

Figure 1 shows the metabolic rate of each subject when his body temperature had become stabilized in water at different temperatures. The metabolic rate of every man began to increase when the temperature of the water was lowered below about 33° C, but the rise was much steeper with the thin than with the fat men, whose metabolic rates rose steeply only in water below 12° C. The figure also shows that the men's metabolic rates rose when the water temperature was increased above 34° C.

TABLE 1. The heights, weights, skin-fold thicknesses, surface areas and immersed surface areas of the men (Subjects numbered in order of their mean skin-fold thicknesses.)

Subject	Height (cm)	Weight (kg)	Skin-fold thickness (mm) Biceps	Subscapular	Abdomen	Subcostal	Mean	Total surface area (m^2)	Surface area immersed (m^2)
1	173	69	4·1	7·1	7·8	7·2	6·5	1·82	1·70
2	162·5	54·5	3·1	8·2	8·6	7·0	6·7	1·58	1·48
3	171	64·5	3·5	9·8	7·8	6·8	7·0	1·76	1·64
4	187	79	3·4	10·2	11·9	8·4	8·5	2·04	1·91
5	170·5	75	4·4	14·0	13·4	13·15	11·2	1·87	1·75
6	168	69	4·9	13·5	18·9	15·1	13·1	1·78	1·66
7	175	89	9·3	35·4	31·1	30·9	26·7	2·05	1·92
8	170	89	10·5	35·3	28·7	32·9	26·8	2·00	1·87

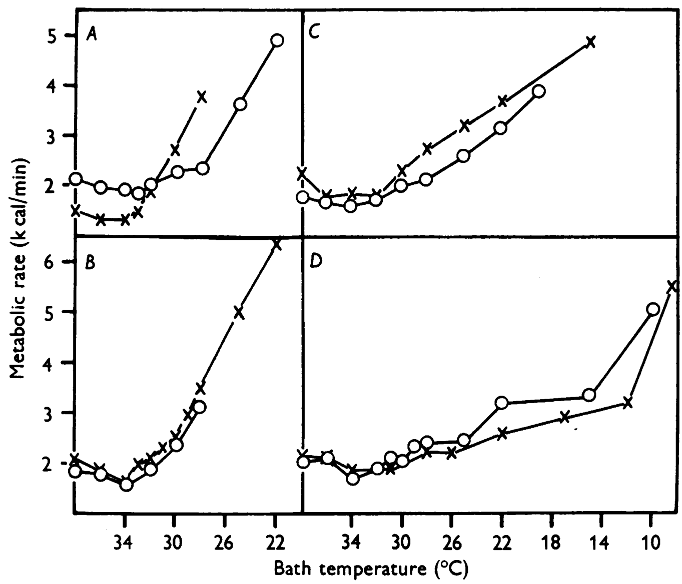

Fig. 1. The effect of the bath temperature on the metabolic rate of fat and thin men in a steady state of heat exchange. Subjects numbered according to fat thickness (higher numbers = fatter men)

Block...		*A*	*B*	*C*	*D*
Subjects	O–O	1	3	5	7
	×–×	2	4	6	8

Figure 2 shows the total body insulation of each subject at various water temperatures. It was at a minimum at the highest temperatures, and this minimum insulation was about the same for all the men, being as low in fat as in thin men. As the water temperature was lowered the insulation rose to a maximal value which was much higher in fat men than in thin men, and was reached at a lower water temperature with fat than thin men. With a further fall in water temperature the insulation fell. This decrease in insulation from the maximal values was of about the same size in all except the two fattest men, whose insulation fell sharply in water below

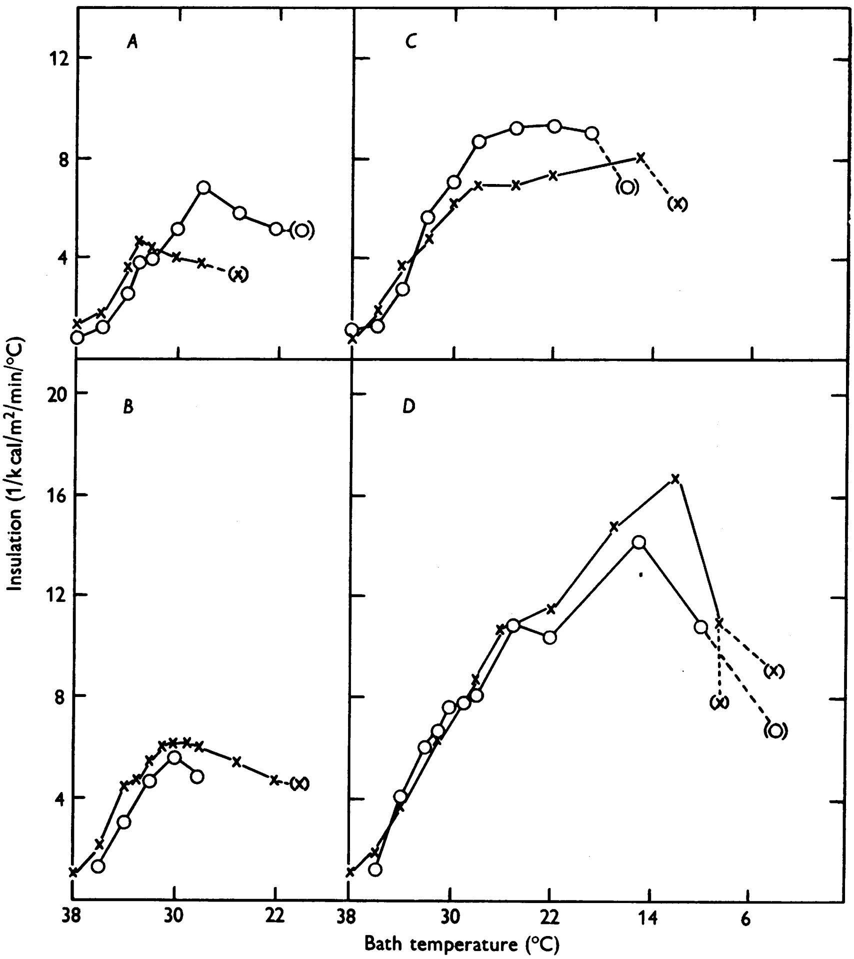

Fig. 2. Total body insulation of fat and thin men in a steady state of heat exchange in relation to bath temperature. Symbols and blocks as in Fig. 1. Brackets indicate approximate values when temperature failed to become stabilized.

12° C. Two values are given for subject 8 in water at 8° C; the higher was obtained when his temperature was stabilized temporarily after 75–90 min in the water, and the lower was an approximate figure calculated after his temperature had begun to fall again.

Figure 3 shows that there was an approximately linear relationship between bath temperature and stable body temperature in all except the fattest men. In the thinner men the slope of the line was generally significantly different from zero when the t test was applied (subject 4, $P < 0{\cdot}005$; subjects, 1, 5 and 6 $P < 0{\cdot}05$). The slope of the line was less steep for the moderately fat than for the thin men, and the two fattest men

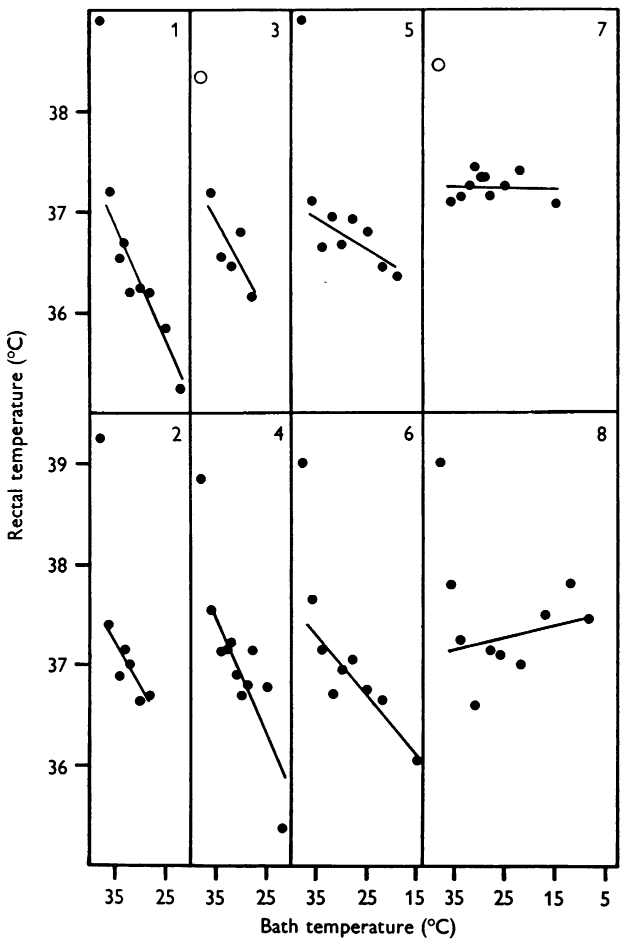

Fig. 3. Relationship between bath temperature and stable body temperature in fat and thin men. Number in each section indicates the subject, higher numbers = fatter men. (○) shows where the experiment had to be terminated before the rectal temperature had become fully stabilized.

showed no tendency to a lower body temperature as the bath temperature was lowered; the temperature of one of them even tended to be higher at the lower bath temperatures. The results from the 38° C immersions were excluded from these calculated lines, as this temperature was higher than the men's normal body temperature and their body temperatures were forced to rise.

Figure 4 gives the rates of heat loss measured by heat-flow disks at various sites when the men's temperatures had become stabilized in water at 38, 31–33 and 22° C. These are expressed as thermal conductivity, as heat loss related to the temperature gradient between the rectum and the bath, in order to facilitate comparisons at different water temperatures. A complete set of readings was taken at all these temperatures in only four men, two of whom were thin and two moderately fat, and the means of these are connected by a line. In water at 38° C thermal conductivity was

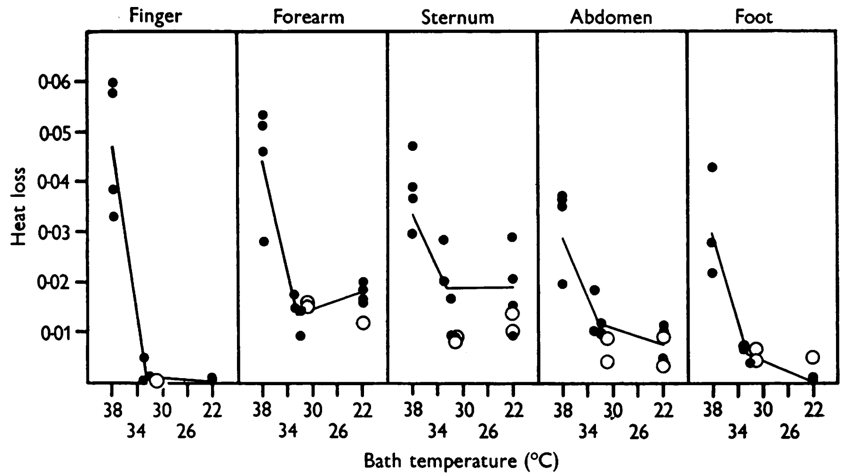

Fig. 4. Heat loss from five sites in a steady state of heat exchange in water at different temperatures. ○, two fattest men; ●, subjects 1, 4, 5 and 6 (the lines connect mean values for these four men). Heat loss shown in cal/cm²/min/° C rectal —bath temperature gradient.

high between the rectum and all parts of the body surface, and was somewhat greater to the finger than to the skin of the trunk. In water at 31–33° C conductivity to all skin areas was lower, but was much lower to the extremities than to the trunk. In water at 22° C heat loss from both the finger and foot was negligible, but thermal conductivities to the skin over the sternum were as high, and those to the skin of the abdomen almost as high, as in water at 31–33° C, while those to the forearm were generally higher at 22 than at 31–33° C. Heat loss from the two fattest men was only recorded in water at 31 and 22° C, when heat loss from their trunk tended to be less than in thin men.

Figure 5 gives the results of an experiment on a fat man (subject 8) immersed in water at 5° C for 80 min. Between 20 and 70 min after immersion his rectal temperature fell slowly but fairly steadily, his metabolic rate increased steadily, and his visible shivering also increased in intensity; this pattern of change was similar to the changes observed when thin men were immersed in water at 20–25° C. Heat loss fell within 40–50 min to fairly low steady values from the trunk, forearm and foot, but in the finger, after falling rapidly at first, it returned in waves and 79 min after immersion reached a level higher than from any other site. When the heat loss from the finger rose to high levels the rectal temperature began to fall more rapidly. At this time the man started shivering intensely and became

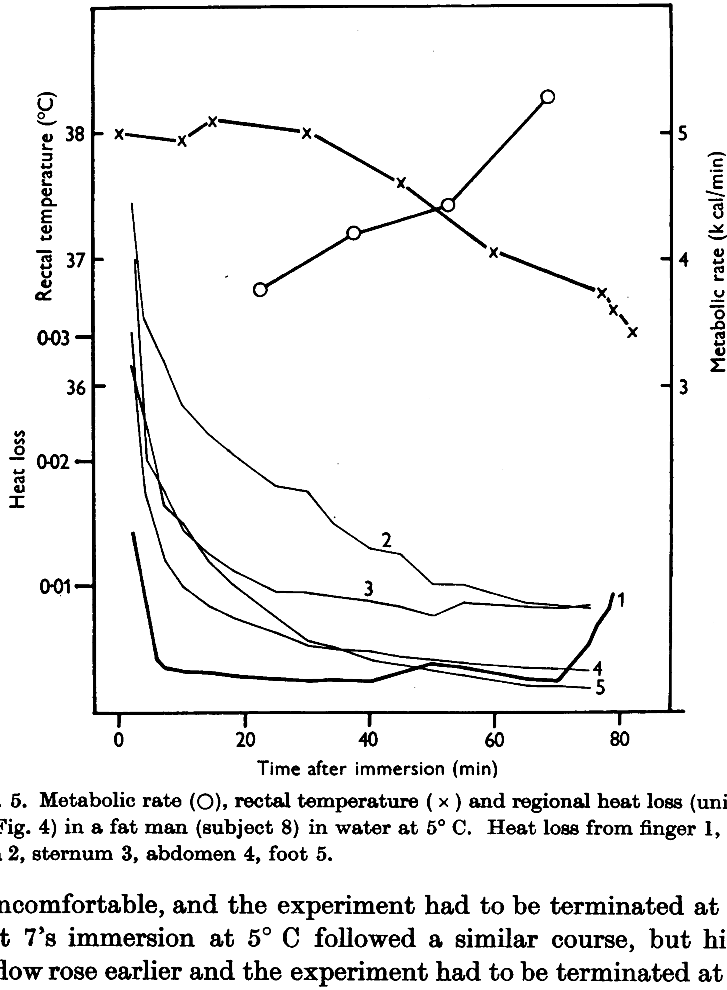

Fig. 5. Metabolic rate (O), rectal temperature (×) and regional heat loss (units as in Fig. 4) in a fat man (subject 8) in water at 5° C. Heat loss from finger 1, forearm 2, sternum 3, abdomen 4, foot 5.

very uncomfortable, and the experiment had to be terminated at 82 min. Subject 7's immersion at 5° C followed a similar course, but his finger blood flow rose earlier and the experiment had to be terminated at 40 min. When subject 8 was immersed at 8·5° C, his temperature became stabilized temporarily between 60 and 75 min after immersion, after which there was a small but distinct cyclical increase in his finger heat loss. His rectal temperature then fell again and did not become stabilized until the experiment was terminated after a total of 105 min. A similar small increase in finger heat loss was observed when subject 7 was immersed at 10° C, but increases in finger heat loss were not observed in immersions at higher temperatures except occasionally, in association with waves of vasodilatation throughout the skin of the whole body.

Table 2 shows the effects of maximal work on the rate of fall of rectal temperature in five subjects immersed at water temperatures at which they were found to be just unable to stabilize their rectal temperature when still. In all cases their temperatures fell more rapidly when they worked than when they were still.

TABLE 2. The effect of work on the fall in rectal temperature of fat and thin men in water just too cold for them to achieve thermal stability when still

Subject	Bath temperature (° C)	Duration of periods of immersion over which comparisons were made (min)	Fall in deep body temperature (° C)	
			Still	Working
1	20	55	1·50	2·25
4	20	55	0·90	2·10
6	12	70	1·35	1·70
7	5	30	0·40	0·65
8	5	30	0·00	0·25

DISCUSSION

Part played by superficial and deep temperature receptors in the metabolic response to cold

The fact that the thin men's rectal temperatures, unlike those of the fat men, were stabilized at a lower level in cold than in warm water provides evidence that stimulation of deep receptors was largely responsible for the fact that they had higher metabolic rates than fat men in a steady state of heat exchange in cold water at a given temperature. It is known (Spealman 1946; Carlson, 1954; Keatinge, 1960*a*) that a change in deep body temperature greatly alters the metabolic response to cutaneous cold. The present experiments therefore confirm earlier evidence (Keatinge, 1960*a*) that the adjustment of the metabolic rate of individuals with differing thicknesses of subcutaneous fat to their widely differing rates of heat loss during prolonged exposure to cold is brought about largely by deep temperature receptors. Observations that the rectal and mouth temperatures of men approaching thermal stability were lower in a cold than a warm room were made by Hardy & DuBois (1938) and by Glaser & Newling (1957), but the fat thickness of their subjects was not recorded by these authors.

The metabolic rates of fat as well as of thin men in a steady state of heat exchange rose in water below about 33° C, and since the stable rectal temperature of the two fattest men was as high in cold as in luke-warm water, their relatively small increase in metabolic rate in cold water must have been a response to cutaneous cold only. This makes it clear that cutaneous receptors are important in the metabolic response to prolonged as well as to brief exposure to cold and are capable of responding for long periods at an approximately constant low temperature. In the thin men the response to cutaneous cold was clearly reinforced by stimulation of deep receptors, and the fact that the metabolic rate of a fat man (Fig. 5) rose as his rectal temperature fell in water at 5° C shows that deep temperature receptors can be important in raising the metabolic response of fat men, too, during long exposure to really low temperatures.

The concept of 'critical temperature'

Although the fat men increased their metabolic rates in water below about 33° C, they did not achieve their maximum tissue insulation until the water temperature was much lower. Their increase in metabolic rate was therefore unnecessary, in that they could have achieved thermal balance by vasoconstriction alone at these temperatures. Rubner (1902) and Scholander *et al.* (1950) have discussed and made use of the concept of a critical ambient temperature at which an animal's maximum tissue insulation is achieved, and below which the metabolic rate is increased in order to maintain the body temperature. Burton & Bazett (1936) have reported detailed results on one man in water which suggested that for man, too, there was a critical temperature, 33° C in water for their subject, at which he achieved his maximal tissue insulation and below which his metabolic rate rose. The fat thickness of this man was not recorded. In the present experiments only the thinnest men behaved approximately in this way, while for the fat men there was a wide difference between the water temperatures at which their metabolic rate increased (about 33° C) and at which they achieved their maximum tissue insulation (about 12° C). The ambient water temperature below which there is an increase in the metabolic rate of men in a steady state of heat exchange, as defined in these experiments, and for immersions of 1–3 hr, may be described as the 'metabolic threshold temperature' in water. It appears to be about 33° C for both fat and thin young men, at least when they are acclimatized to a temperate environment, and to be determined in such men mainly by cutaneous receptors. The lowest water temperature in which a man could in theory achieve thermal stability without an increase in metabolic rate may be described as the 'theoretical critical temperature' and can be calculated approximately for the present subjects from the individual's lowest metabolic rate, his maximum recorded tissue insulation, and his rectal temperature in water at 33° C. It was as high as 32° C. in one thin man (subject 2) and as low as 22° C in a fat man (subject 8). However, the men would presumably have achieved higher insulations in cold water if they had not shivered, so that these calculations of theoretical critical temperature probably give values that are too high, particularly in the case of the fat men.

The theoretical critical temperature of the present men in air would presumably have been rather lower as a result of the additional insulation provided by the air. Direct evidence about the existence of a critical temperature for naked man in air is somewhat confusing, probably because of the difficulty in obtaining a steady state of heat exchange in air. Men have been reported to shiver in cold air only when their skin temperature falls below about 19° C (Swift, 1932); but Hardy & DuBois (1938) reported that during long exposure naked men showed bursts of shivering in air below about 26° C, while Hardy & DuBois (1940) reported that naked men and women achieved their maximal tissue insulation in still air at 27–29° C.

The critical temperature of naked man in air has also been reported as 28° C on the grounds that men preferred to work rather than to keep still in air below this temperature (Erikson, Krog, Andersen & Scholander, 1956); however, this observation may merely indicate that at this ambient temperature stimulation of the cutaneous cold receptors was sufficient to cause discomfort. Scholander *et al.* (1950) accepting the concept of a critical temperature for naked man and regarding it as 27–29° C in air, considered that this high critical temperature placed man as a tropical animal. The present results suggest that if theoretical critical temperature is used as a criterion this view is an over-simplification.

Effective stimulus to the cutaneous thermoreceptors

Although suggestions, differing in detail, have been made at various times that the thermoreceptors of the body might respond to spatial temperature gradients in the tissues rather than to the level of their local temperature, Hensel & Zotterman (1951) and Hensel & Witt (1959) have shown clearly that the effective stimulus to cold receptors in the tongue was a fall in local temperature. They also review evidence which on balance makes it likely that other superficial thermoreceptors behave in the same way. The present results and those of Keatinge (1960*a*) fit in well with this view: although they do not rule out the possibility that the cutaneous cold receptors might be stimulated in part by spatial temperature gradients as well as by the level of their absolute temperature, they are adequately explained by the hypothesis that both superficial and deep receptors respond principally to the level of their local temperatures, with the superficial receptors showing a limited degree of adaptation to prolonged cold.

Nature of the metabolic response to cold

There is evidence, recently reviewed by Chatonnet (1959), that the metabolic response of adult man to cold is largely brought about by muscular contraction, although this is not the case in cold-acclimatized rats (Cottle & Carlson, 1956). In the present experiments substantial increases of metabolic rate in cold water were accompanied by shivering whose intensity corresponded roughly with the size of the increase in metabolic rate, and it seems probable that the metabolic response to cold in them was very largely brought about by muscular activity.

Rise in metabolic rate at high temperatures

The fact that the men's metabolic rates were higher in water at 38 than at 34° C is in keeping with many previous observations that the metabolic rate may rise when the body temperature rises (e.g. Houghton, Teague, Miller & Yant, 1929). The rise is generally attributed to a higher rate of heat production by individual tissues at the higher temperature. Although this direct effect of temperature on the tissues must play a part, restlessness in the warmer water may also have been important and so also may increased cardiac work due to cutaneous vasodilatation at the higher temperatures.

Blood flow and subcutaneous fat in regulation of heat loss

The fact that fat men could reduce their loss of heat more than thin men in the cold is also in keeping with earlier reports (Winslow, Herrington & Gagge, 1937; Pugh & Edholm, 1955; Baker & Daniels, 1955–6; Carlson *et al.* 1958; Keatinge, 1960*a*). In particular, these experiments confirm the large increase reported by Carlson *et al.* (1958) in the tissue insulation of fat as opposed to thin men as the bath temperature was lowered. The calculations of Carlson *et al.* were based on brief experimental immersions in water, which probably accounts for certain differences between their results and the steady-state values obtained in the present experiments.

The minimum tissue insulation of fat and thin men was about the same. This observation differs from the report of Winslow *et al.* (1937) that a fat man maintained a higher insulation than a thin man in warm as well as cold surroundings, but is consistent with the observation of Miller & Blyth (1958) that fat and thin men showed a similar rise in rectal temperature when they were exposed to external heat or to exercise. It implies that when the fat men were warm they were able virtually to eliminate the insulating effect of their fat by a high cutaneous blood flow. The rate of heat loss in water at 38° C was as great from the extremities as from the trunk in all men in whom it was measured. At water temperatures of about 33° C, however, heat loss from the fingers was very low, and vasoconstriction in them was presumably almost complete in both fat and thin men. Vasoconstriction must, however, have been incomplete elsewhere in the body at this temperature, at least in fat men, since they were able to increase their over-all insulation much further at lower water temperatures.

The over-all tissue insulation of the thin men reached a maximum in water not much colder than 33° C and always fell a little when the water temperature was lowered further. Similar falls were reported by Burton & Bazett (1936) and Carlson *et al.* (1958) and are attributed to an increased muscle blood flow due to shivering. The fact that in the present experiments thermal conductivity between the rectum and the forearm skin was generally higher in water at 22 than at 31–33° C, while thermal conductivity to the skin of the trunk was generally the same or lower at the lower water temperature, suggests that this fall in total insulation was largely due to an increased blood flow in limb rather than trunk muscle. The thickness of subcutaneous fat is known to be less in the limbs than the trunk (Edwards, Hammond, Healey, Tanner & Whitehouse, 1955); and Table 1 shows that this was so as regards the arms of the present subjects.

Cold vasodilatation

Although the over-all insulations of the two fattest men rose to high values as the water temperature was lowered to 12° C, they fell sharply below this temperature. These falls in tissue insulation below 12° C were considerably larger than the falls associated with shivering in the thin men at higher temperatures. Since they were associated with a marked and cyclical increase in heat elimination from the finger they were presumably due mainly to cold vasodilatation. It has been shown previously that cold vasodilatation can take place in the fingers of even generally chilled people (Keatinge, 1957) and is due largely to the direct effect of low temperatures on blood vessels (Keatinge, 1958). The dilatation is not confined to the extremities (Clarke, Hellon & Lind, 1958). The present results show that it can greatly reduce the insulation of fat men in water below about 12° C and they imply that no amount of subcutaneous fat would enable these men to survive in near-freezing water for an indefinite period without external protection. In this they appear to differ from aquatic arctic mammals such as whales and seals, which can certainly survive in near-freezing water for long periods.

Effect of physical exertion on heat loss in cold water

Work in water at 16° C (Pugh & Edholm, 1955) and at 5 and 15° C (Keatinge, 1959) accelerates the fall in rectal temperature of thin men but has little effect on that of fat men at these water temperatures or on that of thin men in water at 25° C. The present experiments show that when either fat or thin men were just unable to stabilize their temperatures when sitting still in water, physical exertion always accelerated their falls in temperature. As suggested previously, this effect of exertion is presumably due to an increased blood flow in muscle, particularly limb muscle. It seems unlikely that physical exertion can ever assist a man to achieve thermal stability during prolonged immersion in water.

SUMMARY

1. The metabolic rate of both fat and thin young men in heat balance in water rose when the bath temperature was lowered below 33° C, although the fat men did not achieve their maximal tissue insulation until the water temperature was much lower. The commonly used concept of 'critical temperature' was therefore not valid in the case of the fat men and alternative terms are proposed.

2. The metabolic rate rose less in fat than in thin men when the bath temperature was lowered below 33° C; the stable rectal temperature of the thin men was lower in cold than in warm water, while that of the fattest men was not.

3. It is concluded that the fat men's small metabolic response to cold was due to reflexes from the skin, while in the thin men these were reinforced by a fall in deep temperature and stimulation of deep temperature receptors.

4. The fat men achieved a higher maximal tissue insulation than thin men and could stabilize their body temperature in water down to 10–12° C. In colder water heat loss from their fingers rose in a cyclical manner, their tissue insulation fell by about 50% and their rectal temperatures fell.

5. Work accelerated the fall in rectal temperature of both fat and thin men in water just too cold for them to stabilize their rectal temperature when still.

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