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GENERAL ACCLIMATIZATION TO COLD IN MEN STUDIED BEFORE, DURING AND AFTER A YEAR IN ANTARCTICA

by

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GENERAL ACCLIMATIZATION TO COLD IN MEN STUDIED BEFORE, DURING AND AFTER A YEAR IN ANTARCTICA

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G. M. BUDD *

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ABSTRACT

Four caucasian men were exposed naked to an air temperature of 10°C for 95 minutes, twice on each of five occasions during a 73-week period in Australia and Antarctica. Throughout this period they sustained considerable cold exposure outdoors, often while inadequately dressed. A highly significant improvement which occurred in their ability to maintain rectal temperature during acute cold stress is attributed to general acclimatization to cold. Heat production and skin temperature did not change significantly although extremity temperatures were generally lower in Antarctica. Tissue insulation appears to have increased owing to changes in the vasomotor response to cold, which may have been mediated by changes in catecholamine metabolism. The degree of acclimatization was inversely related to air temperature but not to the hours of daylight. Its development was apparently slow but its decay was rapid. The small degree of acclimatization remaining six weeks after the cessation of cold exposure rendered the subjects less able to maintain rectal temperature than they had been before acclimatization was first achieved.

INTRODUCTION

Many living organisms, when subjected to repeated or prolonged exposure to thermal stress, develop an improved tolerance to that stress — that is, they acclimatize to it. Poikilothermic (1) and homeothermic (2, 3, 4) animals have been shown to acclimatize to heat and to cold. Man has been shown to acclimatize to heat (5, 6, 7, 8), but whether he can acclimatize to cold is still a disputed question.

Many studies seeking evidence of human acclimatization to cold have been carried out. The results generally have been contradictory. Following a period of exposure to cold, the subject's ability to maintain deep body

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temperature (usually measured in the rectum) during acute cold stress has been found to be enhanced (9, 10), unchanged (11, 12), and diminished (13). The metabolic response to cold has been observed to increase (14), to remain unchanged (12), and to decrease (13, 15, 16). Skin temperature during cold stress has been found to be raised (12, 14, 17), unchanged (13, 18), and lowered (19).

These conflicting results have led some observers to conclude that man does not acclimatize to cold, and two plausible suggestions have been advanced to account for his failure to do so. Man, as an animal whose original habitat was the tropical forest, might already have reached the limits of his physiological adaptation to cold in moving to "temperate" climates (20), so that "normal" man is in fact almost maximally cold-acclimatized. Alternatively, man's clothing and housing might be so efficient that even in cold climates he can maintain a "tropical microclimate" next to his skin (21, 22). Studies of the skin temperature of clothed Lapps (23) and Eskimos (24) have given support to this view. It has been pointed out that exposure to the almost lethal temperatures used to acclimatize small animals (such as rats and rabbits) to cold in the laboratory is so unpleasant that man rarely, if ever, voluntarily tolerates such a degree of cold stress; therefore we cannot expect to find acclimatization to cold in man, except in exposed parts of the body such as the hands and face (21).

Despite the reasonableness of both these views, it is also possible that the conflicting results may be due in large part to the variety of methods used both to induce acclimatization and to test for its presence. In attempts to induce acclimatization, different workers have exposed men, naked or clothed, in the laboratory or in the field, to different conditions of temperature, wind and radiation for different periods of time, sometimes continuously and sometimes intermittently — and when the exposures have been intermittent there have been differences in their duration and frequency, and in the conditions in which the subjects have lived between cold exposures. The conditions of the experimental cold exposure used to test for the presence of acclimatization have varied with regard to duration, clothing, activity and diet; to air temperature, air movement, radiant temperature and humidity; and to many other factors which can affect the results. The body size, fatness, and physical fitness of the subjects have also varied. When one considers that even the substitution of a canvas mattress for an open-mesh mattress, or the addition of a pillow, can change the subject's response to the cold environment (as was observed during preliminary experiments before the commencement of the present study), it is hardly surprising that there is at present no consistent body of evidence for human acclimatization to cold.

It is of interest to review the main approaches that have been adopted in studying this problem. In one group of studies, attempts have been made to acclimatize men by means of controlled exposure in cold rooms, on the lines of the procedure successfully used to acclimatize men to heat. Naked volunteers have been subjected to continuous (25) or intermittent (26, 27) exposure in cold rooms for periods as long as 31 days. In one of these studies (26) there was a decrease in shivering, heat production and rectal temperature, in another (27) there was only a decrease in rectal temperature, and in the other (25) there was no change in body temperature or heat production. Possible explanations of this lack of agreement are that acclimatization to cold takes more than 31 days to develop, or that a different pattern of exposure, such as very frequent brief exposures, might be more effective (10). These speculations serve to emphasize the difficulty of attempting to acclimatize men in cold rooms when it is not known what kind of exposure is likely to be most effective.

An alternative approach is to study men living in cold climates, on the assumption that their clothing and shelter will not always provide adequate protection from the cold. As mentioned above, this assumption has been disputed, but it appears to be justified at least in the case of poorly-dressed people such as the aborigines of central Australia and the Indians of Tierra del Fuego. Comparative studies have been made of these and other racial and cultural groups (28 to 38), and several interesting differences between groups have been noted, but as Hammel (28) has pointed out, two serious problems are inherent in such comparative studies. It is difficult to obtain samples of subjects fully representative of their parent populations, since the numbers inevitably are small and the range of variation between individuals is large; and the results cannot answer the question whether acclimatization to cold can be acquired by man, since any differences observed may well be hereditary.

These problems can be largely avoided by means of the longitudinal study, in which the same subjects are studied at intervals before, during and after exposure to cold. This design permits study of the development and decay of any changes observed, and the disturbing effects of differences between individuals are removed by the fact that each individual acts as his own control. The problem of obtaining a representative sample remains, but it affects only the application of the results to the general population, not the interpretation of the particular results themselves.

In recent years a number of longitudinal studies have been made of caucasian men living in temperate or cold climates. Two groups of subjects living in Kentucky were studied at monthly intervals for six months, and decreased shivering and heat production were observed in the colder weather (18). Several groups of military personnel stationed in Arctic America were studied for periods ranging from four or more weeks (12, 16, 39) to four months (13). In the longest study (13) decreases in rectal temperature and heat production were observed; in another (16) there was a decrease in shivering but not in heat production; and in the others (12, 39) there was only a rise in skin temperature, which in at least one case (39) was largely the result of increased physical fitness rather than cold exposure.

The members of polar expeditions, who leave a temperate climate to spend one or two years in a very cold climate, have also been studied. Such men frequently remark on their improved tolerance to cold as the year progresses, and a number of investigations have been carried out in search of a possible physiological basis for these subjective impressions. For example, subjective reports by Frazier (40) and Butson (41) indicated that men did not increase their clothing as much as might be expected when the weather became colder. Goldsmith (42) therefore kept records of the clothing worn throughout a year at Shackleton (lat. 78°S), and found that subjects compared at equal levels of cold stress before and after midwinter wore less clothing in the second half of the year yet were not less comfortable. Palmai (43) obtained similar results in the wet-cold climate of Macquarie Island (lat. 54°S). These results, although susceptible to other interpretations, might be regarded as suggestive evidence of general acclimatization to cold.

The distinction between general and local acclimatization, although of uncertain validity, is a useful one. Local acclimatization of the hands, in the form of an increased resistance to the numbing effect of cold winds, was first demonstrated, in Canada, by Mackworth (44), who later showed (45) that this local acclimatization could be artificially induced by 4 weeks of short daily exposures in a cold room. Massey (46), using the same technique, observed that the increased resistance to numbing developed within 6 weeks of arrival in Antarctica.

Physiological investigations of any complexity are difficult to carry out in the Antarctic, owing to the primitive working conditions, the isolation, and the problems of organization of subjects and assistants that face an observer working alone. Since the observer is usually the medical officer of the expedition, physiological work can be done only when medical duties permit, and at any time it can be interrupted or indefinitely postponed by the occurrence of an accident or illness. Moreover, if the investigation is one which repeatedly imposes an unpleasant experience on the same subjects over a long period of time, it may be hard to keep their cooperation throughout the psychological stresses of a year in the Antarctic.

An experimental procedure frequently used in studies of general acclimatization is to expose men to cooling of the whole body in air for an hour or two, during which time their heat production, rectal temperature, and skin temperature at various sites are measured. The simultaneous measurement of all these variables, and the maintenance of standard environmental conditions in every test cold exposure, are not easy even in favourable conditions, and so it was not until 1957 that a study of general acclimatization by means of these methods was carried out in the Antarctic. In that year Milan (15), the physiologist with the American International Geophysical Year party at Little America III (lat. 78°S), exposed eight naked subjects to an air temperature of 17°C for 2 hours in autumn, winter and spring. The main findings were that in winter and spring the skin temperatures were higher, and the heat production in response to the cold exposure lower, than they had been in the autumn; the rectal temperature remained unchanged throughout the exposure in each group of experiments. The autumn experiments, done 5 weeks after the expedition had arrived at Little America, were the first ones in the investigation, as it had not been possible to conduct control experiments while the subjects were still in temperate latitudes.

The problem of control studies, to establish the "normal" response for comparison with responses observed later in the Antarctic, is an awkward one. In the first month or two after arrival in the Antarctic there is generally little time available for conducting experiments, and by the time the first experiments are done the subjects' responses may already have changed. Nor is it easy to conduct experiments on the same subjects before they leave their home country, or again after their return, for these are usually times when subjects and observers are extremely busy with matters other than physiology, and are often living in different parts of the country. There are also difficulties of interpretation when control studies are made in the northern hemisphere, for it is winter at the time most expeditions depart and return; and if they travel by sea they experience a variety of environmental conditions in their long passage from the northern winter, through the tropics and the southern summer, to the cold Antarctic summer.

These difficulties of interpretation, at least, are absent when Antarctic expeditions are mounted from countries in the southern hemisphere. When Australian expeditions arrive in Antarctica in January, they encounter average air temperatures some 40°F lower than the summer temperatures experienced in Melbourne a few weeks previously. During the next 6 months the average monthly air temperature falls by a further 30°F and the colder temperatures are accompanied by strong winds, drifting snow and darkness. After midwinter the sequence of events is reversed, until in the autumn of the following year the men once more arrive back in the warm climate of Melbourne.

This steady progression through a range of 70°F in average monthly air temperature, over a 17-month period, appears to offer a favourable opportunity for the study of acclimatization to cold. The variation in climate is large, yet the rate of change is gradual enough to allow time for a slowly-developing physiological change to mature. Experiments to assess men's reactions to cold can be commenced in Melbourne when the ambient temperature is over 60°F, repeated at various levels of climatic stress in the Antarctic, and concluded in Melbourne after the return of the expedition.

My appointment as medical officer with the 1959 party of the Australian National Antarctic Research Expeditions (ANARE) to Mawson provided the opportunity to undertake such a series of experiments. The purpose of the study, carried out at Mawson and Melbourne between 1958 and 1960, was to ascertain, by means of serial exposures to a standard acute cold stress, whether men's reactions to cold altered during their 17-month tour of duty. Any changes noted were to be critically examined as possible evidence of acclimatization to cold. The relation of such changes to the level of climatic stress prevailing at the time of each experiment was to be assessed, and the physiological mechanisms involved were to be identified if possible.

A brief preliminary account of this study has already been published (47).

THE ANARE STATION, MAWSON

Mawson (lat. 67°36′S, long. 62°53′E) is situated on a small rock exposure on the coast of Mac.Robertson Land, in the Indian Ocean quadrant of the Antarctic continent (Fig. 1). Named after the Australian Antarctic explorer Sir Douglas Mawson, it has been continuously occupied by successive parties of the ANARE since its establishment in February 1954. Each party sails from Melbourne in late December or early January, and returns some 15 months later. General accounts of ANARE activities, and of Mawson station, have been published by Law & Béchervaise (48) and by Swan (49), and an account of the year 1959 at Mawson by Béchervaise (49a).

The wintering party carries out a broad scientific programme in the fields of meteorology, geophysics, geology, glaciology, cartography and biology. The size of the Mawson party has varied from 10 men in 1954 to 33 men in 1960; in 1959 there were 23 men. Between 1956 and 1960 local air transport facilities were provided by members of the R.A.A.F. Antarctic Flight wintering at Mawson, but since the loss of four aircraft in less than 12 months in 1959-1960, transport facilities once again have been limited to tracked vehicles, dog sledges and man-hauled sledges.

Thermal environment at Mawson

Indoor. The living quarters and most of the huts in which men work are heated, indoor temperatures generally being in the vicinity of 68°F.

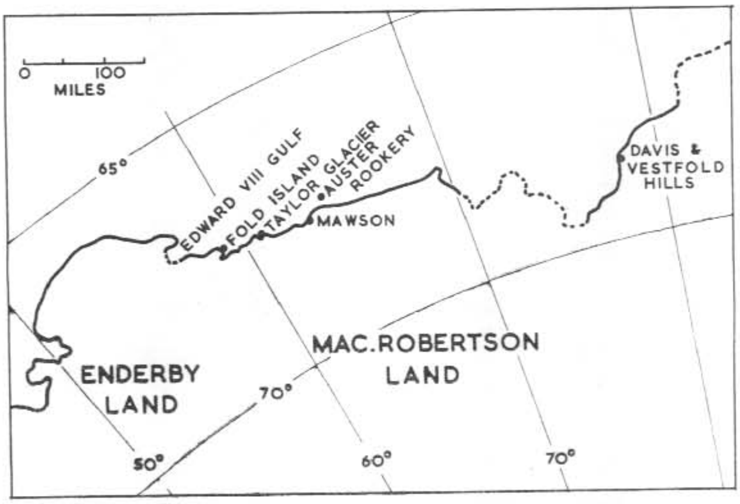

FIG. 1—Map of Mac.Robertson Land, Antarctica.

Outdoor. The main features of the Mawson climate in 1959 are shown in Fig. 2 and Table A1*. It can be seen that in the warmest month the mean air temperature was below 32°F and in the calmest month the mean wind speed was over 17 m.p.h. The mean annual temperature and wind speed were 12.5°F and 22 m.p.h. respectively, and the extreme temperatures were 42°F and —28°F. The windiest months were those in which the lowest temperatures occurred, and for most of the year the stronger winds were accompanied by drifting snow. Thirteen major blizzards occurred during the year. The maximum wind velocity in any month was never less than 74 m.p.h., and in five months of the year it exceeded 100 m.p.h. Conditions inland, to which the subjects were intermittently exposed in the course of field work, were more severe.

These conditions contrasted strongly with those encountered in Melbourne immediately before the departure of the expedition and after its return; on both these occasions the mean air temperature was approximately 63°F.

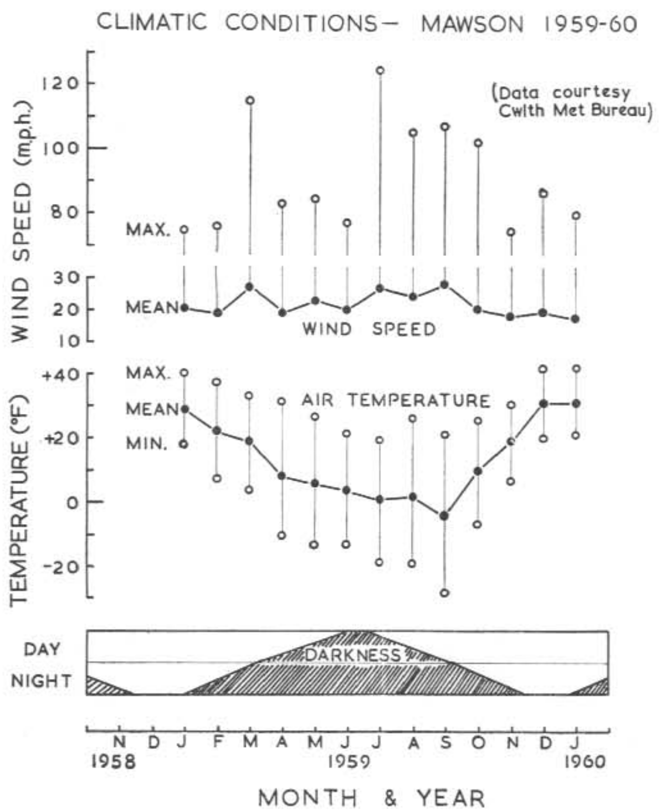

FIG. 2—Climatic conditions at Mawson, 1959-1960.

* Tables prefixed with "A" are set out in the appendix (pages 75-85).

Exposure to cold at Mawson

It is a truism that men are unlikely to become acclimatized to cold if they avoid being exposed to it. In the polar regions men usually live in heated dwellings and wear protective clothing when outdoors; it is therefore important to consider how much time they spend outdoors, and how much protection they obtain from their clothing at such times. Unfortunately it is impossible to generalize about the amount of cold exposure experienced on a typical polar expedition, because the "typical" polar expedition no longer exists. The 35 stations at present occupied in Antarctica are characterized by a great diversity of latitude, housing, organization and activities. All of these factors influence the amount of cold exposure experienced, and estimates of cold stress must be based upon a knowledge of the particular circumstances at the station under consideration and the activities of the particular subjects. It therefore becomes necessary to describe conditions at Mawson in some detail.

Latitude. The latitude of an Antarctic station exerts a profound influence upon the seasonal pattern of cold exposure of its inhabitants. At stations in high latitudes the extreme cold (sometimes colder than −100°F) and the prolonged darkness of winter restrict outdoor activity to a much greater extent than they do at coastal stations not far south of the Antarctic circle, such as Mawson. At Mawson there are several hours of twilight adequate for outdoor work even in the midwinter period when the sun does not rise, and such work therefore continues throughout the year.

Design of the station. Many Antarctic expeditions are housed either in a single all-purpose hut or in a number of huts connected by passageways, and in some cases the entire station is buried beneath the surface of the snow. At such stations it is possible for men to remain indoors for days or even weeks at a time without inconvenience, and to choose periods of favourable weather for any outdoor excursions they may wish to make.

At stations as decentralized as Mawson the situation is very different. Fig. 3 and Fig. 4 show that the station consists of more than two dozen huts scattered over a wide area. Snow accumulation is rarely greater than that shown in Fig. 4. The six-man sleeping huts, and the latrine hut, are mostly within 50 yards of the mess hut and the recreation hut, but the huts in which men work are at distances varying from 30 to 400 yards. Because of this decentralization, it is impossible for men to ignore the outdoor environment; in the most sedentary day's work there are at least a dozen occasions on which men must expose themselves to the weather, and in the average day's work there are more than a score of such occasions, even for men whose work is mostly indoors. Since this movement between huts must continue in all weathers, most huts are linked together by the "blizzard line" (Fig. 5), a stout rope fastened to steel bars fixed in the rock which serves for guidance and support. Because of the unfavourable terrain and the relatively short distances, vehicles are not used for transport about the station, even though in blizzards it may take more than 10 minutes to walk a few hundred yards. Putting on and removing windproof outer clothing dozens of times a day soon becomes tiresome, and so one finds that unless a blizzard is blowing most men do not bother to wear cap, gloves, or windproofs for walks of less than 100 yards. The continual wind rapidly dissipates the heat stored in the clothing, with the result that men are superficially chilled by the time they arrive at their destination. It is possible that repeated brief but intense exposures of this kind could be an effective stimulus to acclimatization.

Organization of the expedition. At Mawson in 1959 no distinctions were drawn between scientists and support personnel, hence the cold exposure associated with the routine camp duties was shared by all men. These duties consisted of general maintenance of the station, supplying the various huts with water and fuel, and disposing of waste; additional tasks in the early part of the year were unloading the expedition ship, sorting stores, and building huts.

At some stations a degree of mechanization is brought to these routine tasks, but at Mawson in 1959 they were accomplished almost entirely by manual labour. The huts were heated by coal-burning stoves, so that sacks of coal had to be dragged or carried 50 yards or more from the dumps. Water was obtained by cutting snow into blocks, by means of a hand saw and spade

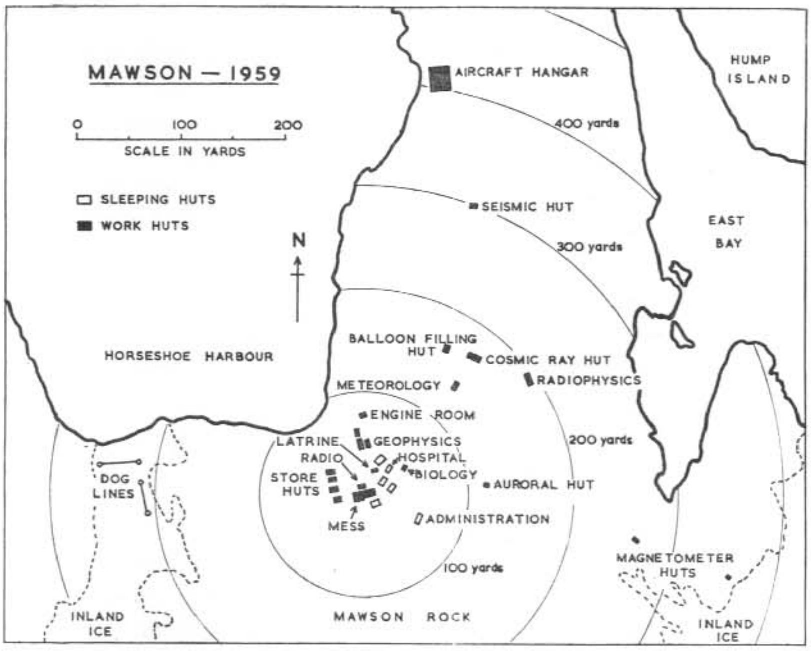

FIG. 3—Map of Mawson, 1959. The concentric circles, at 100-yard intervals, are centred on the mess hut.

ANARE photo G. M. Budd

FIG. 4—Mawson in the spring of 1959, looking north-east. In the centre foreground, behind the pyramid tent, is the mess hut. In the left background is the aircraft hangar, and in the right background the meteorology and cosmic-ray huts.

ANARE photo G. M. Budd

FIG. 5—Mawson in the winter of 1959, showing the blizzard line and, between it and the radio mast, a coal dump. Just visible through the drifting snow are the meteorology hut, on the crest of the hill behind the men, and the balloon-filling hut on the left of the radio mast.

ANARE photo E. L. Macklin

FIG. 6—Water supply at Mawson. Snow is being sawn into blocks outside a sleeping hut. The blizzard line is visible in the foreground, drifting snow in the background.

(Fig. 6), and carrying it by hand to the indoor melting-tanks. Waste water was disposed of by carrying it in buckets for 50 to 100 yards to the dumping site. These duties were shared by the group of men using each particular hut, but in addition there were two daily routine duties that were rostered among all men except the cook, namely the duties of cook's assistant, and nightwatch.

Each duty fell due every 22 days, on the average. The cook's assistant spent about an hour outdoors attending to fuel and water supply and waste disposal. The time occupied by these tasks tended to be longer in bad weather owing to the difficulty of movement outdoors under such conditions. The nightwatch had to visit all parts of the station at midnight, 3 a.m. and 6 a.m., each round necessitating a walk of more than half a mile; in particularly severe blizzards the farthermost hut, the aircraft hangar, would sometimes be omitted, reducing the distance walked by several hundred yards. Observations of the aurora had to be made every 15 minutes, often interrupting strenuous indoor tasks such as scrubbing floors; hence the observer would often be inadequately dressed, and sometimes stripped to the waist, during the minute or so spent outdoors making the observation. The nightwatch's other duties, such as emptying the latrine buckets and replacing the fuel and water used during the night's domestic chores, necessitated further outdoor exposure to cold.

Scientific programme. The scientific programme at some stations is restricted to observatory work, and men may spend a year there without ever venturing outside the station area. At some others there is a field programme which is restricted to the summer months.

At Mawson the scientific programme calls for outdoor work in geology, glaciology, biology and mapping, often in areas remote from the station, in all seasons of the year. In particular, studies of the emperor penguin (*Aptenodytes forsteri*), which breeds in winter, necessitate journeys of 80 to 500 miles, usually by dog sledge, in midwinter and spring (52, 53).

Although scientific work in the field is usually uncomfortably cold, the cold stress of travelling itself is very variable, quite apart from variations in the weather. Men travelling by sledge are constantly in the cold but are usually active. Men travelling by mechanical means are usually sedentary but the interior of the vehicle may be warm (for example the Weasel) or cold (D4 and Ferguson tractors). Even within a given vehicle the cold stress may vary: the driver of a Weasel is hot, but the navigator, whose upper body projects through a trapdoor in the roof, is cold. The maintenance of vehicles and the care of dogs are usually cold work, and the interiors of tents and of many caravans are cold except when cooking is being done.

Protection afforded by clothing. It has long been recognized that efficient clothing can do much to protect men from cold environments (54), and recent studies have shown that Eskimos dressed in fur clothing are exposed to little cold stress (24). Eskimo clothing, however, provides much greater insulation than does the clothing commonly used on polar expeditions (21). Milan (15) has found that heavily dressed men working outdoors in Antarctica sustained large losses of stored body heat, and measurements of the skin temperature beneath the clothing of men (including subject M of the present study) travelling by dog sledge have confirmed this finding. It appears, therefore, that the Antarctic climate does impose considerable cold stress on men working outdoors.

It may be concluded that, as a result of the particular conditions of housing and organization at Mawson in 1959, all men daily experienced many brief cold exposures for which they were often inadequately dressed, and experienced longer exposures at less frequent intervals. These exposures continued in all kinds of weather and in all seasons of the year, and represent the irreducible minimum of cold exposure at this station. The cold exposure experienced by men whose occupations compelled them to be outdoors for long periods of time, such as the four subjects of the present investigation, was superimposed upon an already high general level of cold stress, which itself might well have been sufficient to induce some degree of acclimatization to cold.

METHODS

Experimental design

Four members of the 1959 Mawson party were exposed to a standard test cold exposure before, during and after their year in the Antarctic. Five series of these test exposures were carried out, two of them in Melbourne and three at Mawson. In every series the same four subjects were exposed twice, making eight exposures per series and forty exposures for the whole study. The time and place of each series are shown in Table 1.

Table 1.—The time and place of each series.

Series	*Place*	*Season*	*Date*
1	Melbourne	Summer	December 1958
2	Mawson	Autumn	April 1959
3	Mawson	Spring	September 1959
4	Mawson	Summer	December 1959
5	Melbourne	Autumn	April 1960

The expedition sailed for the Antarctic in late December 1958 and returned to Melbourne in late March 1960. Exposure to cold was slight after leaving Mawson in mid-February 1960, and Series 5 commenced five weeks later, within a week of arrival in Melbourne (Table 2).

Table 2.—The time relations of the more important events in the investigation.

Date		*Event*
1958	December 4-22	Series 1
	December 26	Departure from Melbourne
1959	January 10	Arrival in Antarctica
	January 27	Relief operation commenced
	April 21-30	Series 2
	September 7-25	Series 3
	December 3-14	Series 4
1960	February 16	Departure from Mawson
	March 1	Departure from Antarctica
	March 19	Arrival in Melbourne
	March 25-April 4	Series 5 (Subjects A, B, M)
	April 26 and 28	Series 5 (Subject S)

Subjects

The four subjects were men of European descent who were considered likely to experience considerable cold exposure in the Antarctic. Three of them had wintered in the Antarctic before: Subject B in 1953 and 1955, Subject M in 1952 and 1955, and Subject S in 1954 and 1957. They all preferred to dress lightly in the cold, and habitually led active lives. Their ages and occupations are shown in Table 3.

Table 3.—Characteristics of the subjects.

Subject	*Age** (yr)	*Occupation*	*Height* (cm)	*Weight†* (kg)	*Surface†* *area* (m^2)	*Skinfold‡* *thickness* (mm)
A	29	Surveyor	175	68.5	1.84	12.6
B	49	Officer-in-charge	175	78.0	1.94	19.7
M	34	Radio Operator	178	88.9	2.07	18.8
S	46	Geologist	170	63.5	1.74	8.5

* Age in September 1959.
† Average of the five series.
‡ Average of eight sites, December 1960.

Body weight and skinfold thickness

The subjects were weighed under standard conditions at the time of each series of test cold exposures. They were weighed naked, by means of a beam balance, after emptying their bladders. The results are set out in Tables 3 and 4.

Table 4.—Variations in body weight (kg) of the subjects.

Subject	*Series* 1	2	3	4	5	*Mean*
A	67.1	68.0	70.3	68.5	68.5	68.5
B	78.0	76.2	79.8	76.2	80.3	78.0
M	93.4	88.4	87.1	87.1	87.5	88.9
S	62.6	64.0	64.0	62.6	63.5	63.5
Mean	75.3	74.2	75.3	73.6	75.0	74.7

Skinfold thickness was measured only on one occasion, in December 1960, no suitable caliper being available before that time. A spring-loaded caliper measuring to 0.001 inch was used. The mean value of five successive measurements at each of eight sites was recorded. The results at each site are shown in Fig. 7, and the average of the eight sites in Table 3. The body

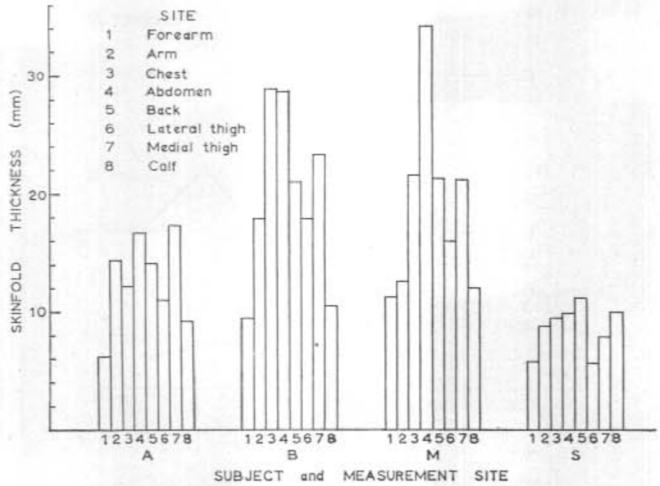

FIG. 7—The pattern of skinfold thickness in each subject.

weight of the subject in December 1960 was equal to his average for the five series in the case of Subjects A and B, 2.7 kg heavier in the case of Subject M, and 1.4 kg lighter in the case of Subject S. During the study, therefore, skinfold thickness would probably have been a little less than the observed values for Subject M and a little greater for Subject S. The rank order of the subjects' skinfold thickness is not affected by these differences.

Physical fitness

Recent reports (27, 39, 55) that changes in physical fitness affect human responses to cold make it desirable to obtain some estimate of the variations in the subjects' physical fitness during the present investigation. Unfortunately no tests of physical fitness at the time of each series were made, but after return to Australia a retrospective assessment was made by reference to diary entries and to memory. Although the limitations of such subjective assessments are obvious, it is felt that men who lead active lives are capable of making reasonably accurate judgments concerning gross changes in their level of physical fitness, and that these assessments, in the absence of any other means, may be accepted here as a reasonable index.

These impressions of physical fitness were graded with reference to each subject's estimate of his own average level, and arbitrary numerical values assigned as follows:

Well above average	+2
Just above average	+1
Average	0
Just below average	−1
Well below average	−2

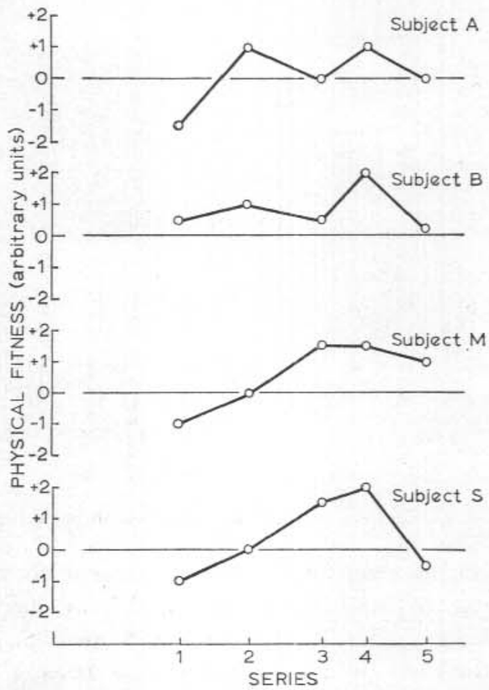

FIG. 8—Subjective estimates of the changes with time in the physical fitness of the subjects. The distance between series is proportional to time.

The results of this subjective assessment of physical fitness are plotted in Fig. 8. It can be seen that the physical fitness of all subjects increased in the Antarctic, and declined somewhat during the five-week voyage back to Australia.

Thermal history of subjects

Indoor environment

The subjects spent considerable periods working in unheated store huts, in which the air and wall temperatures depended upon outdoor conditions. By contrast, on a couple of occasions they worked in very hot conditions. The indoor environments to which the subjects were most constantly exposed, however, were those set out in Table 5. Although the number of observations is small, the values shown are considered to be typical of those prevailing throughout the year.

Cold exposure

Subject A. This subject was a surveyor. His secondary duties were hut building and assisting with the care of the dogs. He was also in charge of field equipment, which was stored in an unheated hut. A complete reorganiza-

Table 5.—The principal warm environments to which the subjects were exposed at Mawson in 1959.* The observations were made at random throughout the year.

Designation of hut	*Number of observations*	*Air temperature (°F)*		*Subjects using hut*
		Mean	*Range*	
Administration hut	12	63	49-71	A (working) B (sleeping and working)
"Ross" sleeping hut	16	68	60-78	A, M, S (sleeping and working)
Radio hut	7	67	64-75	M (working)
Mess hut	16	69	61-74	All subjects
Recreation hut	21	67	54-75	All subjects

* Coal-burning stoves and electric convection heaters were adjusted by the occupants of huts to suit themselves. No thermostats were used.

tion of this hut, which he carried out between June 24 and July 22, constituted his most intensive period of cold exposure.

His field work was divided into two parts. Within a 15-mile radius of Mawson he made a detailed survey by triangulation, mainly during the months of May, August and October. This work entailed servicing and driving an unheated open vehicle, building cairns, and using a theodolite. Servicing of vehicles was done outdoors. The other part of his field work consisted of the determination, by means of astronomical observations (an "astro-fix"), of the position of landmarks, mostly inland, to which he was usually flown. This work entailed standing still for many hours, and his hands and feet were always uncomfortably cold at such times.

In the first three months of the year he spent most of his working time outdoors, although in March there were alternating exposures to blizzard and to temperatures of more than 100°F, in the course of work on a new engine-room and garage that was being built at Mawson. After the destruction of this building by fire on April 3 there followed two weeks of prolonged exposure to cold during the construction of another engine-room, before the test cold exposures of Series 2 on April 24 and 30.

The period before Series 3 (September 22 and 25), when this subject and Subject S were working at the ANARE station, Davis, was also characterized by alternating exposures to heat and to cold. From August 23 to 29 he was mostly outdoors, in temperatures as low as —25°F, and camped out for three nights; between August 29 and September 20 (when he was flown back to Mawson) he worked mostly indoors, with occasional excursions of a few hours at temperatures as low as —30°F; and for five days during this period (September 8 to 12) he worked for 4 to 10 hours daily in the engine-room at Davis, wearing shirt and overalls, in temperatures of 90°F to 115°F with low humidity.

He was not much troubled by the heat. Between the first and second test cold exposures in Series 3 (September 22 and 25), he had two days of prolonged outdoor work at Mawson.

A period of field work also preceded Series 4 (December 4 and 5). From November 16 to 24 he was camping at Edward VIII Gulf and doing astro-fixes on the high plateau in Enderby Land. On December 1 he was flying and later hunting seals near Mawson, and on December 2 he had a long and cold day doing an astro-fix at Baillieu Peak, 50 miles inland, in a 20-knot wind at 15°F. On December 3 he attempted an astro-fix at McNair nunataks, 30 miles inland, but was only in the cold for 1½ hours, being defeated by cloudy weather.

The astro-fix at McNair nunataks was eventually accomplished between January 10 and 14, 1960. Transport on this occasion was by dog sledge.

Subject B. This subject was officer-in-charge of the 1959 Mawson party. He visited all huts in the station on most days. His additional duties as storeman necessitated long periods either working in unheated huts or driving a Ferguson farm tractor that was not fitted with any form of protection from the wind; these duties continued throughout the year, but were particularly pressing in the first three months.

During the period preceding Series 4 (December 12 and 14) he was exposed to greater and more prolonged cold stress than were the other three subjects. From November 3 to 20 he participated in a tractor journey to a point 40 miles inland; temperatures were 15°F to 20°F lower than at Mawson, and he felt cold for much of the time. From December 8 to 10 inclusive he spent 3 to 4 hours daily studying snow crystals in an igloo 40 miles inland; air temperatures in the igloo were 14°F, about 15°F lower than at Mawson.

Subject M. This subject was a radio operator, and his principal duties would therefore be classed as indoor activities. However, his secondary duties as dog man and assistant biologist ensured frequent and prolonged periods of outdoor work at all seasons of the year. A few details of this work are worth recording.

The sledge dogs were tethered in the open more than 200 yards from the mess hut. Their food consisted mainly of seal meat, hence seals had to be hunted, shot and brought back to the station, sometimes from as far as 12 miles away. The frozen meat was chopped up with axes as required. Much time was spent in digging out seal carcasses that had been buried under several feet of snow and ice.

The dogs had to be fed every third day, and generally cared for, regardless of weather conditions — in fact the care required increased as the weather worsened. During blizzards they were visited at frequent intervals to ensure that they were not suffering; any dogs showing signs of deterioration were led or carried to the shelter of one of the station huts, where they were fed and cared for until the weather improved. The amount of outdoor cold exposure sustained by Subject M and his helpers can be gauged from the fact that by the end of one winter blizzard (that of July 26 to 29) there were 14 dogs in huts all over the station (including the hangar 400 yards north-east of the mess hut) and six more remaining on the dog lines 200 yards west of the mess hut. During this blizzard the successive 24-hour-average wind velocities were 50, 78, 50 and 42 m.p.h., with recorded gusts to 124 m.p.h., heavy drift and snowfall, and air temperatures between 0°F and 7°F.

Whenever time and weather permitted, the dogs were taken on short training runs within a 12-mile radius of the station. In addition to these excursions, Subject M participated in four field trips. In the winter he camped at the emperor penguin rookeries at Fold Island and Taylor glacier from June 8 to 12, transport being by air, and during the first 12 days of July he visited the Auster emperor penguin rookery by dog sledge, covering a distance of some 80 miles. He felt cold throughout this journey.

He revisited the rookeries at Fold Island and Taylor glacier between October 17 and 28, covering a distance of 200 miles by dog sledge.

Between January 10 and 14, 1960, he visited McNair nunataks by dog sledge in company with Subject A, covering a distance of 55 miles; he felt comfortably warm throughout the journey.

Subject S. This subject was a geologist. His secondary duties as glaciologist and messing officer necessitated a continuously high level of cold exposure throughout the year. As glaciologist he made regular observations on the sea ice and on the inland ice at distances of up to a mile from the station. As messing officer he carried to the mess by hand, from store huts more than 20 yards away, all the food eaten by the 23 men at Mawson throughout the year. He also carried out, in all weathers, the frequent maintenance required by the unheated store huts, the outdoor food stacks, and the ice-cave on the inland ice where deep-frozen stores were kept. He dressed lightly; his feet were cold when he was outdoors, but otherwise he usually felt comfortably warm. He was the navigator on many long aerial mapping flights, the temperature inside the aircraft's cabin generally being well below 32°F.

The period when he was most continuously exposed to cold was in the month before Series 3, when he spent long periods making a geological survey, on foot, of the Vestfold Hills near Davis. Unlike Subject A, he did not spend any time in the hot engine-room.

On his other field excursions transport was by air. This work was severely curtailed by the loss of the expedition's two aircraft in late December 1959, so that his only overnight camps were from November 22 to 24, when he was working with Subject A on the plateau in Enderby Land.

He had to visit New Zealand immediately after his return to Australia from Mawson, with the result that his test cold exposures in Series 5 were done 3 to 4 weeks later than those of the other subjects.

Test cold exposures

The Melbourne experiments were conducted in a refrigerated room made available by the Commonwealth Scientific and Industrial Research Organization's Division of Building Research. At Mawson the experiments were done in the hospital hut, which was warmed to the desired temperature by means of electric convection heaters. These heaters, one of which incorporated a small fan, provided a uniform air temperature with minimal air movement.

The air temperature was read every 5 minutes during the test cold exposure from a thermometer mounted at the level of the subject, and the mean value for the exposure period calculated. Relative humidity was determined with a whirling psychrometer immediately before and after each exposure and the mean value calculated. Air movement and the mean radiant temperature of the surroundings ("wall temperature") were measured immediately after each exposure, in the position vacated by the subject, by means of a kata-thermometer and a globe thermometer (56). The same calibrated thermometers were used in every series.

The average ambient conditions achieved in each series of test cold exposures are set out in Table 6. The air temperature was close to the intended value of 10°C in all series, but the mean radiant temperature of the surroundings was lower at Mawson than in Melbourne as a result of the cold weather, which chilled the walls of the hut in which the experiments were conducted. A measure of compensation, however, was provided by the lower air movement in the Mawson exposures. Although such small differences in the ambient conditions might be considered unlikely to produce measurable differences in physiological response, it was thought desirable to obtain a quantitative estimate of their effect upon the test cold stress. The observed values for air temperature,

Table 6.—Ambient conditions during the test cold exposures. Mean values of the eight observations for each series.

	Observed values				*Thermal stress* (kcal/m²/hr)*		
Series	*Air temp* (°C)	*Mean radiant temp* (°C)	*Air movement* (cm/sec)	*Rel. humidity* (%)	*Radiation* (R)	*Convection* (C)	R + C
1	10.4	11.4	18	65	68	57	125 ± 3.4†
2	10.3	9.8	4.5	37	74	28	102 ± 0.8
3	10.0	8.1	5	31	80	31	111 ± 6.5
4	10.0	10.0	4.5	38	73	29	102 ± 3.7
5	10.7	11.5	11.5	70	68	45	113 ± 8.5

* Heat loss to the environment as calculated from the equation of Haines & Hatch (57), assuming for all series a mean skin temperature of 28.6°C and a surface area of 1.81m².
† Mean and standard deviation.

air movement and mean radiant temperature in each exposure were therefore substituted in the equations of Haines and Hatch (57):

$$R = eK\ Ar\ (T_w^4 - T_s^4),$$
$$\text{and } C = 2.1\ V\ (t_s - t_a),$$

where R and C are the rates of heat loss to the environment, in B.TH.U./hr, by means of radiation and convection respectively, e is the emissivity of the skin (assumed to be unity), K the universal radiation constant, Ar the effective radiation area of a man (taken to be 15.5 sq. ft.), T_w and T_s the mean radiant and skin temperature respectively in °F absolute, V the air movement in ft./min, and t_s and t_a the skin and air temperature in °F. An assumed mean skin temperature of 28.6°C was used in all calculations, and the surface area was assumed to be 1.81 m^2 for the purpose of expressing the results as kcal/m^2/hr.

The object of this computation was to obtain, not a precise estimate of the thermal exchange between subject and environment, but an index of the relative stress of the environment in the various test cold exposures. The resultant values, summarised in Table 6, show that the total cold stress was virtually identical in Series 3 and 5, and also in Series 2 and 4 at a somewhat lower level. The effect of these variations upon the results of the test cold exposures was examined by means of the analysis of covariance.

In order to exclude the possibility of a qualitative effect of the radiation component of cold stress upon the response of the subjects, the observed values for mean radiant temperature were examined, by means of the analysis of covariance, for their effects upon the main results of the investigation. The effect of the variation in relative humidity, which was lower at Mawson than in Melbourne, was also examined in this way.

Experimental procedure

All experiments were done in the morning, after the subject had had a good night's sleep (with one exception, as described later). The subjects were cautioned to avoid all exertion between the time of waking and reporting at the laboratory some two hours later. Breakfast, eaten shortly after waking, was restricted to fruit or cereals, with fruit juice, tea or coffee. The subjects usually defaecated after breakfast, so that the rectum generally would have been empty during the experiments. A high degree of co-operation was maintained by the subjects throughout all series.

When the subject arrived at the laboratory, thermistors were taped to standard sites on the abdomen, lumbar region, medial thigh, ball of thumb and ball of great toe. A rectal thermistor mounted in a stiff catheter was inserted to a depth of three inches beyond the anal verge. A mask for the collection of expired air was fitted and tested for leaks. The subject then undressed and lay, wrapped in enough blankets to keep him comfortably warm, on a mattress of nylon netting suspended 20 inches from the floor, for the next hour, during the last 30 minutes of which the pre-exposure observations were made. This period is termed the "warm phase" of the experiment. At the end of this time all blankets were rapidly removed, and for the next 95 minutes (90 minutes in Series 1) the subject lay quietly on the net mattress, naked but for a short pair of cotton underpants. This period is termed the "cold phase" of the experiment (Fig. 9).

As a precaution against bladder discomfort during the cold exposure, the subject usually urinated before lying down, and sometimes again before the cold exposure commenced. On such occasions (and also during the cold exposure when necessary) he rolled into the lateral position and used a bottle, without undue exertion or difficulty. In most instances, however, the cold exposure was completed without marked bladder discomfort and the bottle was not required. No fluids were drunk between breakfast and the conclusion of the cold exposure. Urinary output was not measured during the first three series, but following the occurrence of a brisk diuresis in Subject S during Series 4 the volume of urine passed was measured on several occasions.

At the conclusion of the cold exposure the subject dressed and walked to the mess hut or canteen, where he ate a light lunch. After lunch he returned to the laboratory, where final readings of rectal, abdomen and thigh temperature were made and the time noted. The thermistors (which had remained in place from the cold exposure) were then removed. This period is termed the "rewarming phase" of the experiment. No attempt was made to control his activity or diet during this period, but the routine followed was similar on each occasion. At Mawson lunch consisted of hot soup and a dish which usually included meat, instead of the hot drink and light snack taken in Melbourne. In Melbourne, however, the subjects walked further to their meal, in much warmer weather, and in clothing which had not been left in the cold room to become chilled as it had at Mawson; these factors would tend to cancel any difference in the rate of rewarming attributable to the better lunch at Mawson (58), so that gross differences between the two places seem unlikely. Within each place the diet and activity remained constant, hence the rate of rewarming would certainly have been similar in Series 2, 3 and 4 on the one hand, and in Series 1 and 5 on the other.

Skin and rectal temperatures were measured every 5 minutes during the cold phase and the preceding half-hour by means of the thermistors previously described and a null-reading Wheatstone bridge. On all occasions temperatures were read in the same order: rectum, toe, thigh, lumbar region, abdomen, thumb. The time required for a complete round of measurements was between 1 and 2 minutes. In the warm phase the first round of measurements commenced 30 minutes, and the last round 5 minutes, before the blankets were removed. The first round of measurements in the cold phase commenced as soon as the blankets were removed.

ANARE photo J. M. Bechervaise

FIG. 9—Test cold exposure at Mawson. Douglas bags can be seen above and behind the subject, X-ray plant and other medical equipment on the right.

Thermistors were calibrated in a well-stirred water bath before and after every series. The single thermometer used in all calibrations was itself calibrated by the Defence Standards Laboratory in Melbourne in 1958 and 1960. Although the thermometer was accurate to ± 0.02°C, the characteristics of the rectal thermistors were such that this degree of accuracy could not be attained. Rectal temperature was read to the nearest 0.16°C in the first 17 exposures; a fault then developed in the thermistor, and a second thermistor was used for the remaining 23 exposures. This second thermistor was read to the nearest 0.11°C except on the first four occasions of its use, when it was read to 0.21°C.

These limits of accuracy were determined by the slope of the calibration curve for the individual thermistor and the ratio factor of the Wheatstone bridge, and represent the change in temperature corresponding to unit change in the bridge resistance. Temperature readings expressed to the nearest 0.01°C appear strange in the presence of readability as low as 0.11°C to 0.21°C, but it was considered necessary to retain the second decimal in order to preserve equal intervals of temperature for unit change in bridge resistance throughout a given experiment. To have done otherwise would have caused marked distortions in the curve of rectal temperature as a result of rounding errors.

Oxygen consumption was determined every 15 minutes during the exposure period and the preceding half-hour by means of an open-circuit technique using 100-litre Douglas bags and subsequent analysis of samples of expired air. In the warm phase, collections of expired air commenced 30 minutes and 15 minutes before the removal of the blankets; in the cold phase, collections commenced immediately after removal of the blankets, and thereafter at 15, 30, 45, 60, 75 and 90 minutes, but the collection at 90 minutes was not made in Series 1. Collection time was 10 minutes in the warm phase, and also in the cold phase whenever possible; when ventilation volumes were high, however, the Douglas bag was filled in less than 10 minutes. The Douglas bags were tested for leaks before and after every series.

The face-masks used for the collection of expired air were identical with those used in the Integrating Motor Pneumotachograph (59). A perspex expiratory valve of low resistance and a short length of 1″ bore corrugated-rubber hose connected the mask to the Douglas bag. The masks were tested for leaks before and after each collection. The volume of expired air collected was measured within 10 minutes of collection with a Parkinson and Cowan Model D4 dry gas meter. A sample of expired air from each Douglas bag was stored over mercury in a Brodie bottle and analysed for oxygen and carbon dioxide within 24 hours, using a Scholander 0.5 c.c. analyser. A sample of room air was collected half-way through each test cold exposure and the values obtained by analysis of this sample were used for "inspired air" in the subsequent calculations of oxygen consumption, using the method described by Douglas & Priestley (60). The accuracy of the Scholander analyser was verified by means of analyses of outdoor air in every series.

Shivering activity was noted by visual inspection, particular care being given to the determination of the time elapsing before the onset of shivering. These records are somewhat fragmentary, however, for the observers were often occupied with other measurements and so could not watch the subject all the time.

Heart rate was determined, using either the radial or carotid pulse, every 5 minutes during exposures in Series 3, 4 and 5 only.

Subjective impressions during the exposure were noted in an interview with the subject immediately after each exposure.

Analysis of results

Units

Temperature measurements were expressed in degrees Centigrade.

Heat production was expressed simply as oxygen consumption in millilitres per minute. It was felt that to use the respiratory quotient (calculated from the measured carbon dioxide output and oxygen consumption) to estimate the calorific equivalent of the oxygen consumed would be misleading under the varying conditions of body temperature, shivering and hyperventilation encountered during the test cold exposures.

No "correction" for body size was made. The use of body weight and surface area as metabolic reference standards is open to criticism (61, 62) and in the present instance it is unnecessary, since the effects of differences between subjects are eliminated in the analysis of variance. However, in order to facilitate comparison with the results of other workers and with the estimated cold stress of the test exposure, the results for oxygen consumption were converted to $kcal/m^2/hr$ in some instances. An assumed value of 4.92 kcal per litre of oxygen was used, and the surface area was calculated from the subject's weight and height by means of Weir's nomogram (63), itself based upon the formula of DuBois:

$$\text{Surface area} = 0.007184 \times \text{height}^{0.725} \times \text{weight}^{0.425}$$

where weight is expressed in kilograms, height in centimetres, and surface area in square metres (64).

Tabulation and graphical presentation

For each variable the eight exposures in each series were averaged and the results plotted against time in minutes. The two exposures of each subject in each series were averaged and plotted in the same way for case studies, and in a number of instances the results of individual exposures were also plotted.

In addition to these presentations of the time-course of the exposure in each series, all the warm-phase and cold-phase values used in the statistical analysis were similarly averaged for series and for individual subjects in each series. The tabulated results were plotted against time in months, in order to demonstrate the relation between the different variables in the five series.

Variables analysed

The warm-phase variables analysed were the final values for skin and rectal temperature, read 5 minutes before the commencement of the cold exposure, and the average of the two determinations of oxygen consumption made during this phase.

The cold-phase variables analysed were the values for skin and rectal temperature after 90 minutes of cold exposure, and the average of the first six determinations (0 to 80 minutes) of oxygen consumption in this phase.

The measurements made in the warm phase serve a double function. They indicate any changes between series in the physiological response to a warm environment, and they serve as control values for the subsequent response to the test cold exposure.

In experiments of this nature it is always possible that differences observed between cold-phase values may be due, not to differences in the response to the cold exposure, but to pre-existing differences in the warm phase. The absolute value for rectal temperature in the cold phase, for instance, is determined more by the value observed in the preceding warm phase than by the relatively small response to the cold exposure. To overcome this difficulty and evaluate clearly the response to the cold exposure, rectal temperature in the cold phase was expressed as change from the warm-phase value, read 5 minutes before the cold exposure commenced. Skin temperature, by contrast, was expressed as the absolute value, unadjusted for differences between the warm-phase values, since inspection of the cooling curves showed that these differences soon disappeared and seemed to have no effect upon the final values reached.

Metabolic responses are often reported either as net increases (by simple subtraction), or as percentage increases, over initial values. Both methods are open to criticism (65, 66), and the procedure adopted in the present instance was to examine the relation between the values for oxygen consumption in the cold phase and the warm phase by means of analysis of covariance (Table A20). The regression coefficient proving to be non-significant ($P = 0.20$), it was concluded that the cold-phase values had not been appreciably influenced by the warm-phase values, and that no adjustment was required.

Statistical analysis

The results were examined statistically for differences between series and between subjects by means of a two-factor analysis of variance with two replications in each cell (67).

Series. The five series were regarded as standardised tests to measure the effects of five distinct treatments, the treatments being successive periods of residence (of several months) under different levels of climatic stress. The series effects are regarded as fixed effects.

Subjects. The four subjects were not selected by means of a device known to produce randomness, but neither were they consciously selected in any sense likely to make their responses to cold different from those of the general population. However, it is possible that a measure of self-selection is always present in volunteers for Antarctic expeditions, and in any case a group of four subjects is a small sample on which to base conclusions about the general population. The subject effects in the analysis of variance are therefore regarded as fixed effects, and extension of the results of this study to the general population must remain a matter of inference rather than statistical proof (68).

Replicates. The effects of each "treatment" were tested twice on each subject. It is therefore possible that some residual effect of the first test cold exposure in each series could have affected the response in the second test. However, the interval between tests varied randomly from 1 to 7 days (depending upon availability of the subject and observers, power supply, etc.), and so many other uncontrolled factors were present in this period that it is considered unprofitable to regard the replicates as other than random.

Analysis of covariance. In order to investigate the possibility that some of the observed changes might have been related not to acclimatization, but to associated variables, the results were examined by means of the analysis of covariance as set out in Wishart (69), Cochran (65) and Smith (70).

In the case of the analyses in which the affecting variate (x) was the test cold stress, two problems were encountered. The first was that the differences between the treatment means of x (Table 6) were highly significant. However, they were not causally related to the treatments in the sense of being necessary accompaniments, for with better experimental technique they could have been eliminated; they are therefore regarded as being coincidental.

The second problem was that heterogeneous variance was present in x (Table 6). This heterogeneous variance was due to the same cause as the significant treatment differences noted above — imperfect control of the ambient conditions during the test cold exposure. In Series 3, for instance, cold stress inside the test chamber was unusually high on one occasion as a result of the lower "wall temperature" and higher air movement caused by a blizzard that was shaking the building. By contrast, a period of unusually fine weather permitted excellent control of the ambient conditions in Series 2. In Series 5 several divergent values were caused by faults that developed in the refrigeration system during the exposures. Because of this heterogeneity of variance in x, the significance tests in the analyses on cold stress should be regarded as approximate rather than exact.

RESULTS

Statistical summary

Warm phase. The mean values for all the exposures in each series are set out in Fig. 10 and Table A2. The mean values for individual subjects in each series are set out in Fig. 11 and Tables A3-A8.

Table A9 summarises the results of the analyses of variance. There was a significant variation between series in rectal temperature and thigh skin temperature. Highly significant differences between subjects were present in rectal temperature, oxygen consumption and thigh skin temperature.

Cold phase. The mean values for all the exposures in each series are set out in Fig. 12 and Table A10. The mean values for individual subjects in each series are set out in Fig. 13 and Tables A11-A18.

Table A19 summarises the results of the analyses of variance. There was a highly significant variation between series in rectal temperature, and significant variation in oxygen consumption and abdomen skin temperature. Interaction between series and subjects, however, was significant in the case of abdomen skin temperature, and approached the 5% level of significance in the case of oxygen consumption. Highly significant differences between subjects were present in all variables except toe skin temperature.

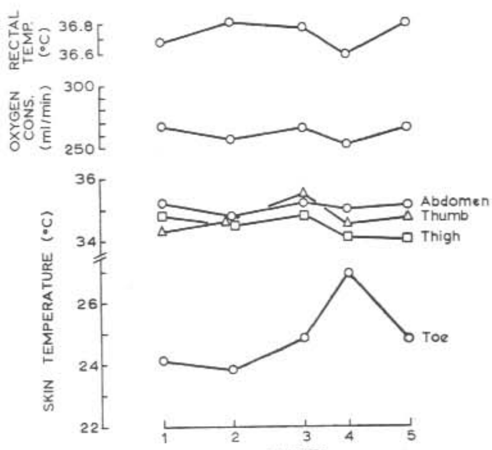

FIG. 10—Warm-phase body temperature and oxygen consumption. Mean values in each series. The distance between series is proportional to time.

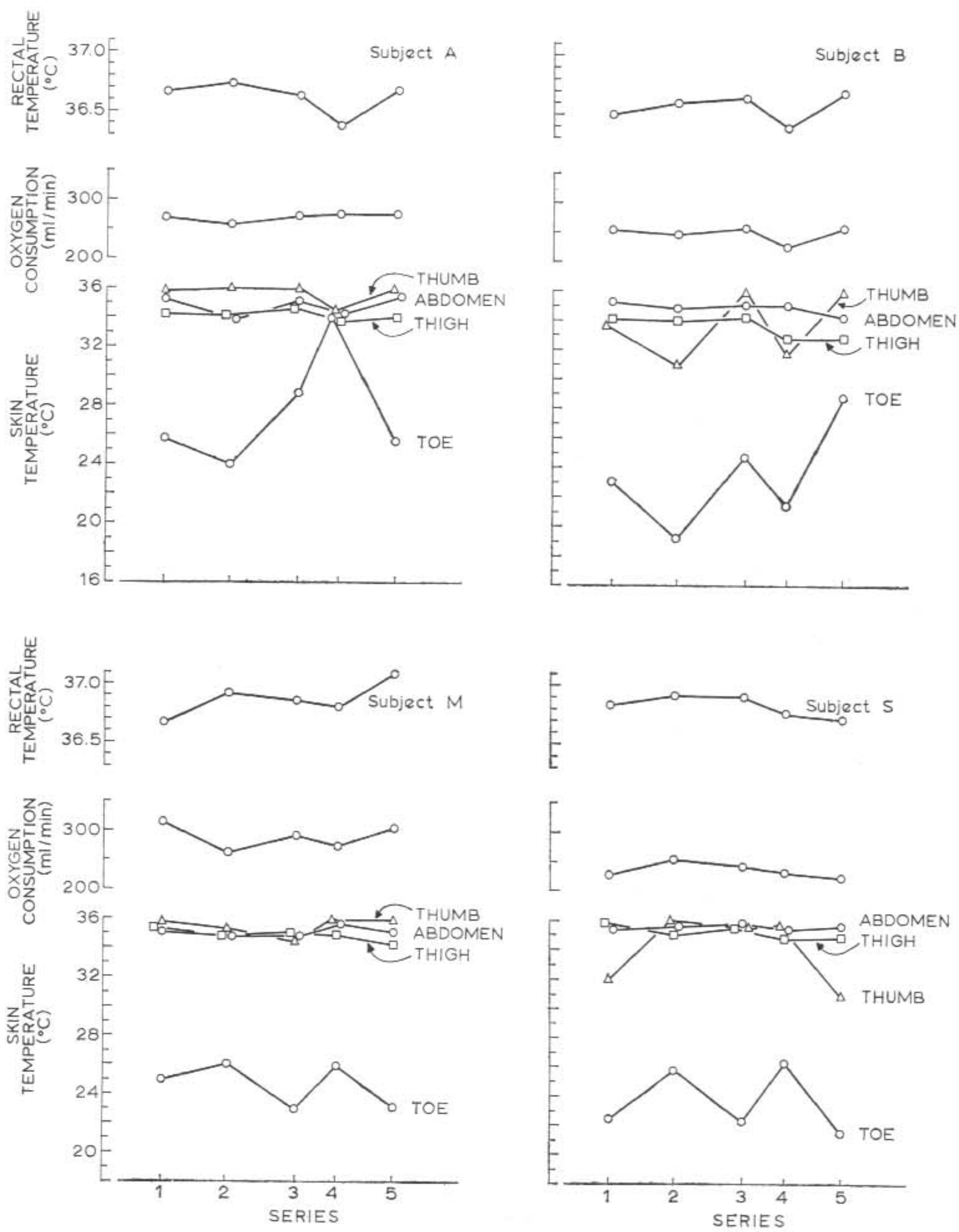

FIG. 11—Warm-phase body temperature and oxygen consumption. Individual values in each series. The distance between series is proportional to time.

Table A20 summarises the results of the analyses of covariance done upon all variables in order to investigate the possibility that the observed changes may have been related to, and possibly caused by, the variations in the test cold stress. The regression coefficient was non-significant in all cases except abdomen skin temperature and possibly (in view of the limited precision of the significance tests) toe skin temperature; the regression coefficients in these two cases were almost identical. The mean values for abdomen and toe skin temperatures, adjusted for variations in the test cold stress, are included in Table A10 and Fig. 12. In the case of abdomen skin temperature, the variation between adjusted series means was non-significant, but the significant interaction and the highly significant differences between subjects remained unchanged. In the case of toe skin temperature, the variation between adjusted series means was still non-significant, although the variance ratio was almost twice as great as in the case of the unadjusted means.

Table A20 also includes the results of the analyses of covariance done to investigate the possibility that the variation between series in rectal temperature may have been related to, and possibly caused by, concomitant variation in body weight or surface area, or variation in the mean radiant temperature or relative humidity during the test cold exposures. In all cases the regression coefficient was non-significant.

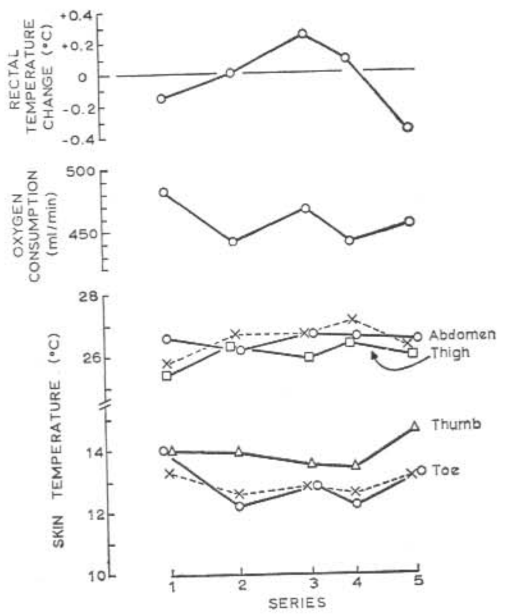

FIG. 12—Cold-phase body temperature and oxygen consumption. Mean values in each series. The distance between series is proportional to time. The observed values for abdomen and toe are shown by broken lines and the values adjusted by analysis of covariance by solid lines.

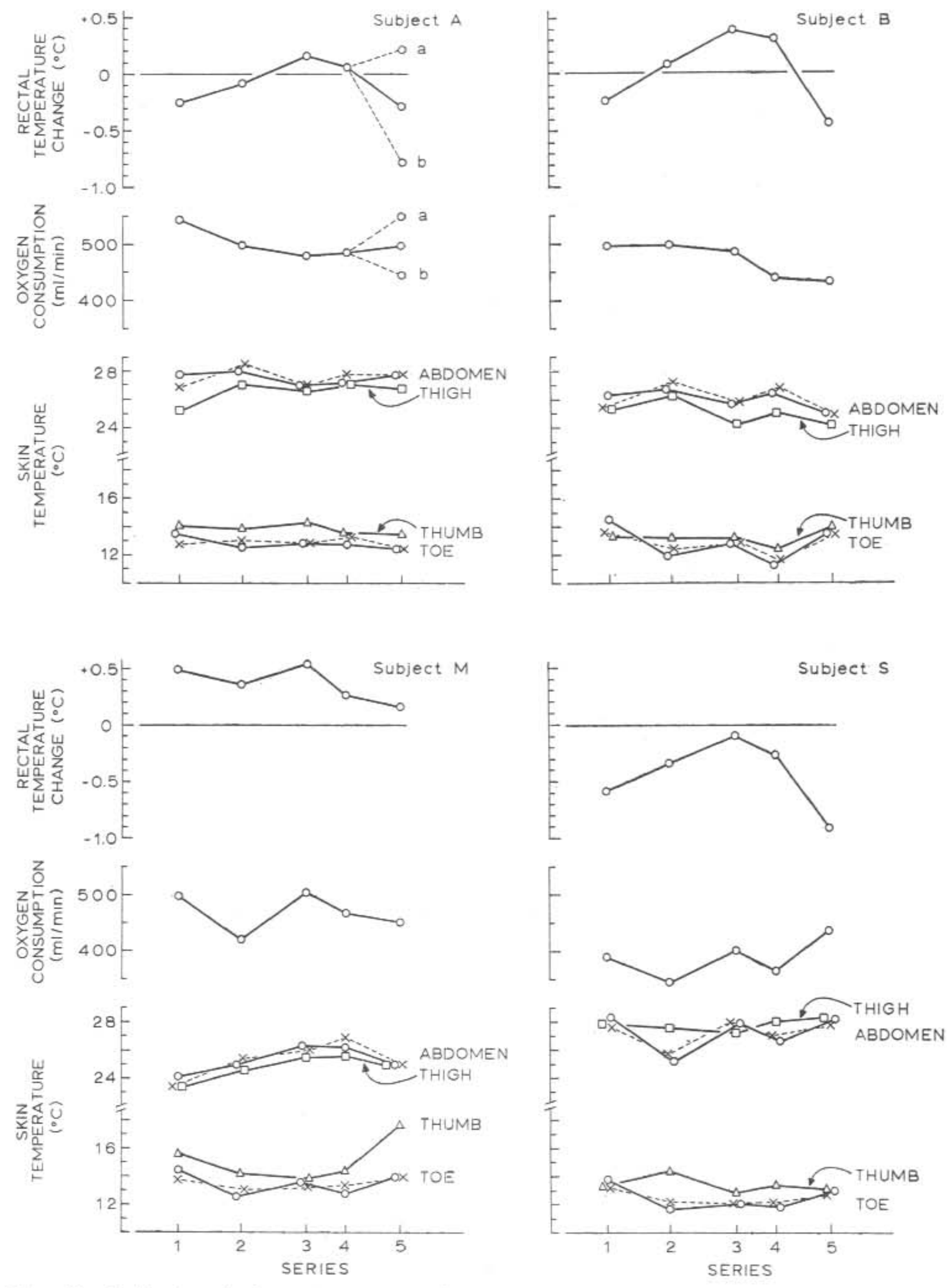

FIG. 13—Cold-phase body temperature and oxygen consumption. Individual values in each series. The distance between series is proportional to time. The observed values for abdomen and toe are shown by broken lines and the values adjusted by analysis of covariance by solid lines. The values for rectal temperature change and oxygen consumption in the first (a) and the second (b) exposure of Subject A in Series 5 are shown as well as their mean.

Rectal temperature

Warm phase. The series means of rectal temperature varied between 36.59°C and 36.80°C (Table A2, Fig. 10). This variation was statistically significant.

Cold phase. The average response of rectal temperature for all subjects in each series is shown in Fig. 14. The differences between series at the 90-minute level are highly significant. It can be seen that in Series 1 the test cold exposure caused an initial fall in rectal temperature, followed by a slight rise which did not regain the pre-exposure value and a secondary fall which reached −0.15°C at the end of the exposure. In Series 3 there was hardly any initial fall and the subsequent rise was early, high and well sustained (+0.25°C at the end of the exposure). In Series 5 there was a slight initial rise of the kind seen in Series 3, followed by a steady fall to a lower value (−0.42°C) than in Series 1. In both pattern and degree Series 2 was intermediate between Series 1 and 3, and Series 4 was intermediate between Series 3 and 5.

The over-all variation between series may be summarised in the statement that the ability to maintain rectal temperature, under the conditions of acute cold stress used in these exposures, improved in Series 2 and 3 and afterwards declined, to the extent that in Series 5 the subjects were less able to maintain their rectal temperature than they had been in Series 1.

The average responses for each subject separately are shown in Fig. 15. Although the general relation between series described above held for the individual subjects, systematic individual differences were apparent in the detailed

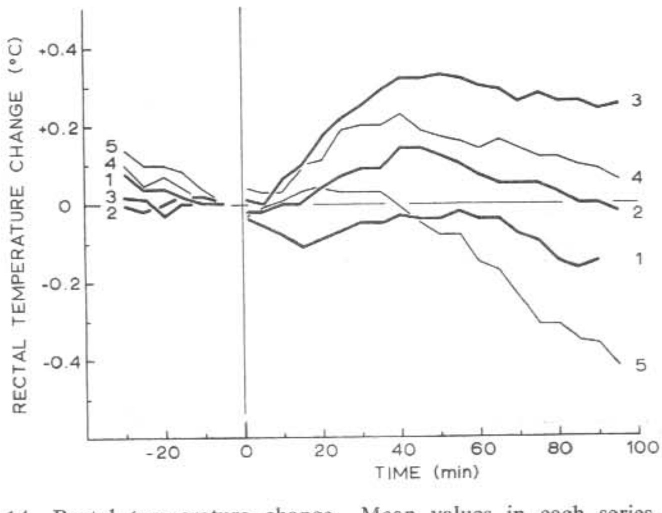

FIG. 14—Rectal temperature change. Mean values in each series. The numbers adjacent to the curves identify the series. Zero time indicates the commencement of the cold phase.

pattern of response and in the degree to which the subject succeeded in maintaining rectal temperature. The ability to maintain body temperature was apparently related to body size, the heavier subjects being the more successful (Table A21).

Anomalous responses. The average values presented, and the statistical analyses, have been based upon all the observations made. They are therefore distorted in certain respects by the effects of three anomalous results, although the general conclusions remain unchanged.

Subject M (the heaviest subject) differed from the others in that his rectal temperature rose in response to the cold exposure in every series (Fig. 15). Nevertheless the time of onset and the slope of the rise varied between series in the same manner as in the other subjects and, with the exception of Series 1, so did the final value reached. In both of Subject M's exposures in Series 1, however, the final value was not (as in the other subjects) intermediate between

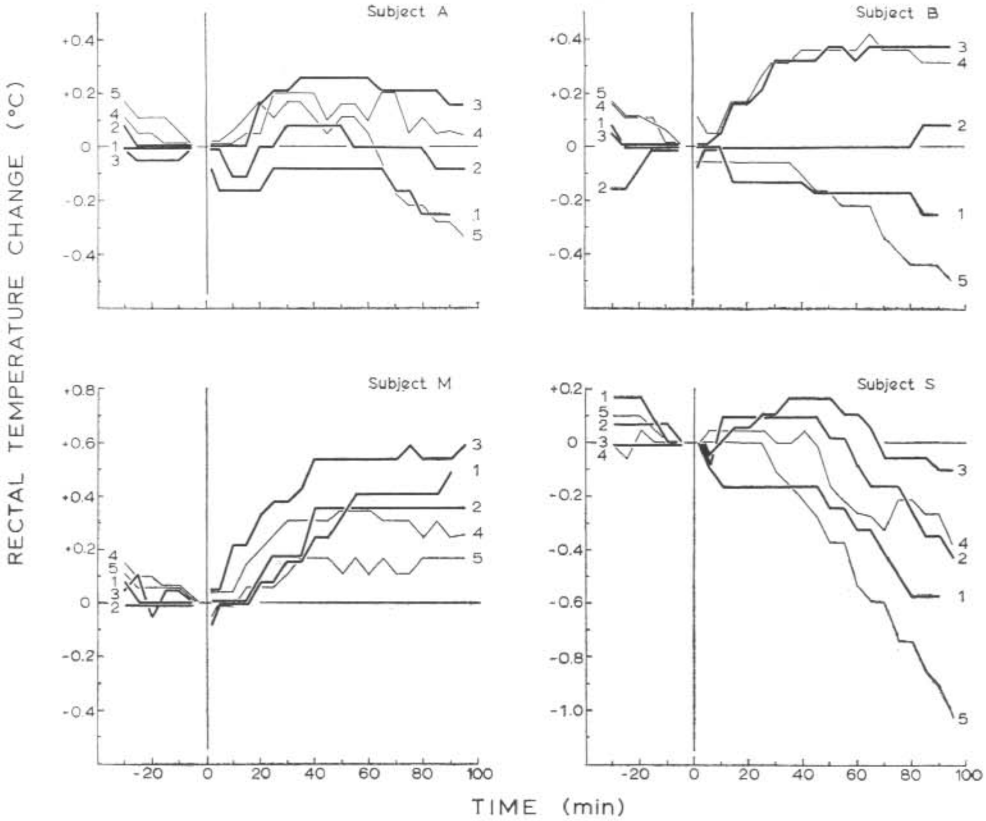

FIG. 15—Rectal temperature change. Individual values in each series. The numbers adjacent to the curves identify the series. Zero time indicates the commencement of the cold phase.

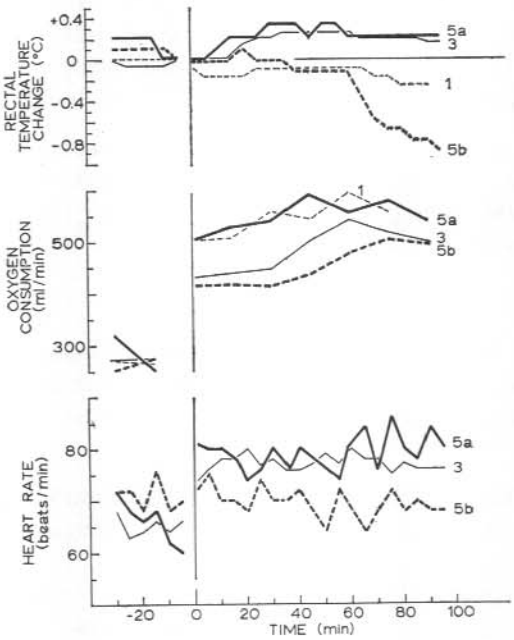

FIG. 16—Rectal temperature change, oxygen consumption and heart rate of Subject A in the two replicate exposures of Series 5, compared with his mean values in Series 1 and Series 3. The numbers adjacent to the curves identify the series. Zero time indicates the commencement of the cold phase.

Series 2 and 5, but was higher than in any other series except Series 3 (Fig. 13). The possible relation of these two anomalous responses to the fact that he was 6 kg overweight in Series 1 (as compared with his average weight in the other four series) will be considered later (page 59). For the present it may be noted that had Subject M, in Series 1, attained the "expected" value (between Series 2 and 5) of approximately 0.24°C instead of the observed 0.49°C, the average value (of eight exposures) for Series 1 would have been −0.20°C instead of the observed −0.15°C.

The difference between the 90-minute values of Subject A's two exposures in Series 5 was 1.00°C (Fig. 13 and 16). Between the other 19 pairs of replicates in this study, the average difference was 0.21°C and the greatest difference 0.54°C. Of Subject A's two responses in Series 5, one (5b) was characteristic of that series, with a 90-minute value of −0.78°C, but the other (5a) was typical of Series 3, with a 90-minute value of +0.22°C. Unfortunately it was not possible to repeat the exposure. The possible relation of this anomalous response to the fact that the subject had only four hours' sleep the previous night will also be considered later (page 64). For the present it may be noted that had the "Series 5" type of response occurred in both exposures, there would have been only a slight early rise in rectal temperature, followed by a steep fall to a 90-minute mean value in the vicinity of −0.78°C, instead of the present mean value of −0.28°C. The difference of 0.50°C would have had the effect of lowering the average (of eight exposures) for Series 5 from the observed value of −0.37°C to −0.50°C.

It can be seen that "correcting" for these three anomalous responses would have had the effect of increasing the over-all variation between series, and between Series 1 and 5 in particular. It would also have reduced the error variance, thereby rendering the variation between series even more significant.

Oxygen consumption

Warm phase. The series means of oxygen consumption varied between 251 and 267 ml/min (Table A2, Fig. 10). The equivalent values for metabolic rate are 39.6 and 41.5 kcal/m^2/hr. This variation was not statistically significant.

Cold phase. The series means of oxygen consumption varied between 440 and 482 ml/min (69.1 and 74.9 kcal/m^2/hr), as shown in Table A10 and Fig. 12. The highest mean value was that of Series 1, and it represents an increase of 81% over the corresponding warm-phase value; this was also the highest percentage increase among the series means. The highest single determination of oxygen consumption in the whole study was 665 ml/min (95.3 kcal/m^2/hr), which represents an increase of 144% over the warm-phase value for that exposure.

The variation between series means was statistically significant, but any generalisation about it would be hazardous, owing to the fact that the interaction between series and subjects approaches the 5% level of significance. This conclusion is supported by Fig. 13, which demonstrates that the variation between series was different for each subject. Two subjects (A and B) showed a small decrease in oxygen consumption throughout the study, the other two did not; in short, no consistent change occurred.

The average response of oxygen consumption for all subjects in each series is shown in Fig. 17, and for each subject separately in Fig. 18. The pattern of response is extremely diverse: the only generalisations applicable to all exposures are that oxygen consumption increased in response to the cold exposure, and that this increase commenced during the first sampling period. On the average, however, oxygen consumption during the first half-hour of the exposure was lower at Mawson than at Melbourne.

Systematic differences of pattern between subjects were apparent in that for Subjects A and B most of the increase occurred in the first three sampling periods, whereas for Subjects M and S oxygen consumption steadily increased throughout the whole exposure period. Systematic differences of pattern between series, on the other hand, were apparent only in the case of Subject S. In Series 1 he showed a slight initial increase followed by a steady rise, whereas

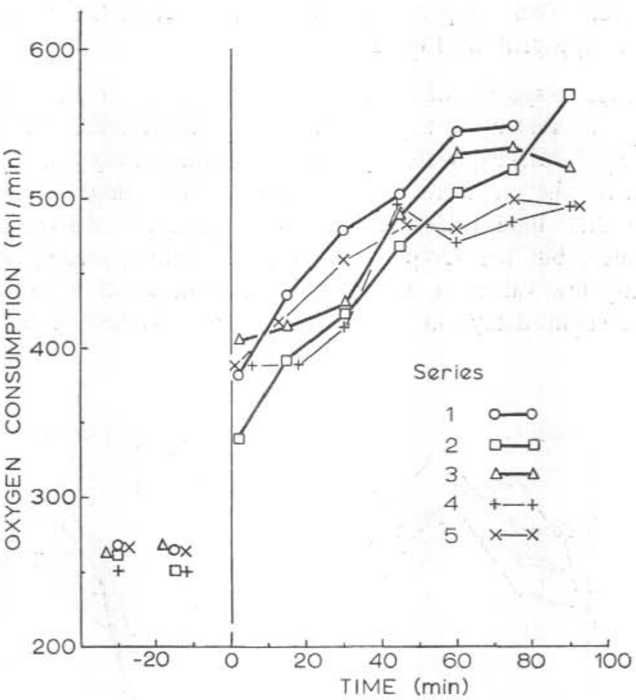

FIG. 17—Oxygen consumption. Mean values in each series. Zero time indicates the commencement of the cold phase. Each value is plotted against the time of commencement of the 10-minute period during which it was determined.

in all subsequent series he showed a greater initial increase which was followed by a decline, often almost to pre-exposure values, before the steady rise commenced.

Skin temperature

The results for lumbar skin temperature were discarded, because of the presence of large and irregular fluctuations caused by variable pressure exerted on the thermistor by the cords of the net mattress.

Warm phase. The variation between series in skin temperature (Table A2, Fig. 10) was statistically significant only in the case of the thigh, where the series means varied between 34.0°C and 34.8°C.

Cold phase. No consistent variation between series in skin temperature was observed, although extremity temperatures tended to be lower at Mawson than in Melbourne (Table A10, Fig. 12). Adjustment for concomitant variation in the test cold stress removed the apparently significant variation between series in abdomen skin temperature, but not the significant interaction between series and subjects (Table A19, Fig. 13). The interaction between series and subjects in thumb skin temperature, which approached the 5% level of significance, is also apparent in Fig. 13.

The average response of skin temperature at each site, for all subjects in each series, is shown in Fig. 19-22. Skin temperature fell steeply in the first 15 minutes of cold exposure and then at a diminishing rate as it approached equilibrium with the environment. Abdomen and thigh temperatures were within 1°C of their final values after 30 to 40 minutes and thumb temperature after 60 minutes, but toe temperature was still falling steeply at 95 minutes. The consistently low values at the 1-minute level in Series 4 and 5 are artefacts resulting from slight delays in making these observations, at a time when the

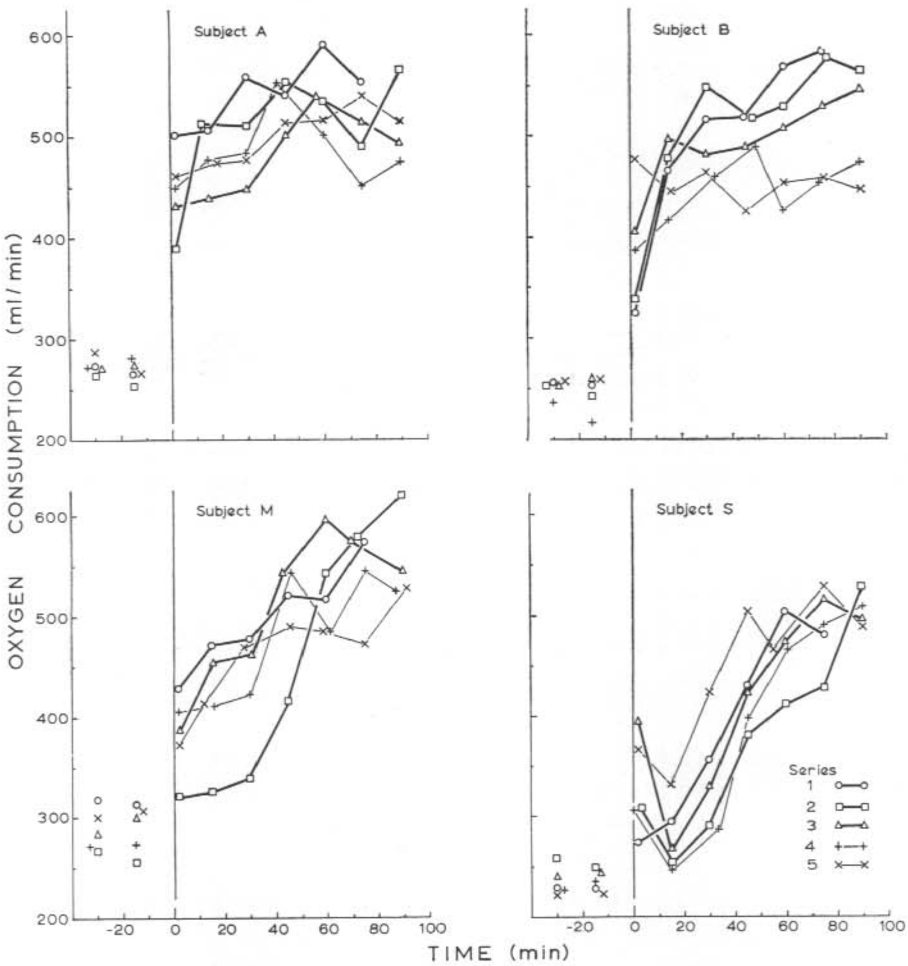

FIG. 18—Oxygen consumption. Individual values in each series. Zero time indicates the commencement of the cold phase. Each value is plotted against the time of commencement of the 10-minute period during which it was determined.

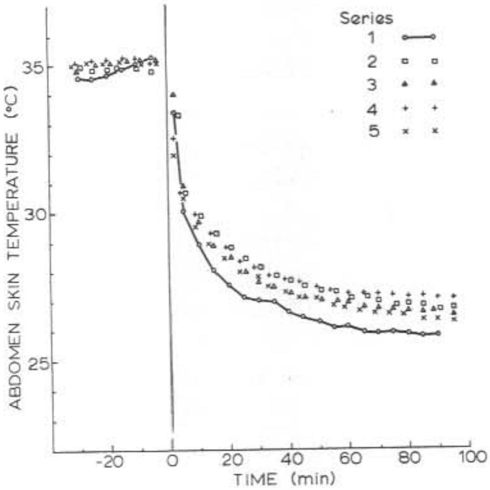

FIG. 19—Skin temperature of abdomen. Mean values (not adjusted by analysis of covariance) in each series. Zero time indicates the commencement of the cold phase.

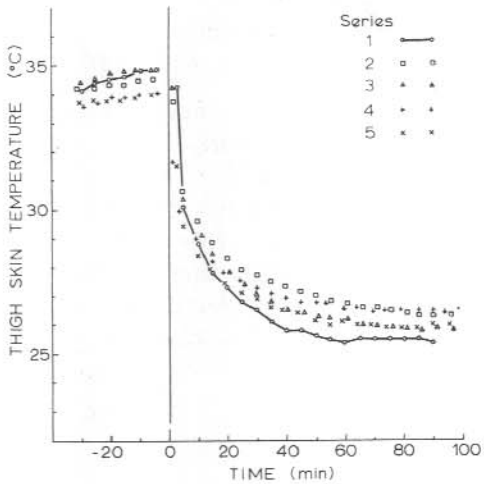

FIG. 20—Skin temperature of thigh. Mean values in each series. Zero time indicates the commencement of the cold phase.

skin temperature was falling rapidly. The average responses for each subject separately were also plotted, and showed that the abdomen and thigh temperatures of Subjects A and S (who ranked lowest in weight and skinfold thickness) approached equilibrium values earlier than did those of Subjects B and M, which showed a more gradual fall.

Shivering activity

Shivering during the cold exposures was very variable, although each subject tended to shiver in a characteristic manner. Periodic fluctuations were observed, as noted by Swift (71) and by Burton & Edholm (72); often a bout of heavy shivering would be followed by a brief period of complete relaxation, during which the subject sometimes experienced no sensation of cold, and sometimes even felt warm — a phenomenon described by Barcroft & Verzár (73) as "basking in the cold". In the initial stages of its development, shivering in the abdominal or intercostal muscles was usually related to respiration, in that the muscle activity occurred only during expiration or at the end of inspiration; a relation to respiration was not observed in the activity of other groups of muscles, such as the quadriceps femoris. On one occasion the first signs of shivering occurred when the subject yawned; he later remarked that yawning always caused him to shiver when he was feeling cold. Possibly this effect represents facilitation of incipient shivering by the involuntary stretching often associated with yawning, similar to the facilitation produced by mechanical stretching of muscle (72). Piloerection occurred intermittently, in various areas of the skin, throughout the exposures. In general, the onset, progression and severity of shivering were reflected in the results for oxygen consumption.

The muscle groups involved in shivering were always those of the trunk or the proximal parts of the limbs; shivering was never observed in muscles distal to the knees or elbows, suggesting that local chilling (which would be most marked distally) does not determine the distribution of shivering. Many kinds of muscle activity were observed, from fibrillation (of varying frequency and amplitude) in single muscles or groups of muscles, to clonic and tonic spasms which produced marked skeletal movement. A distinct "march" of shivering was often observed, two examples of which are set out in Tables A22 and A23. In these two instances the progression was centrifugal, but often the first sign of shivering would be fibrillation in the sartorius or quadriceps femoris.

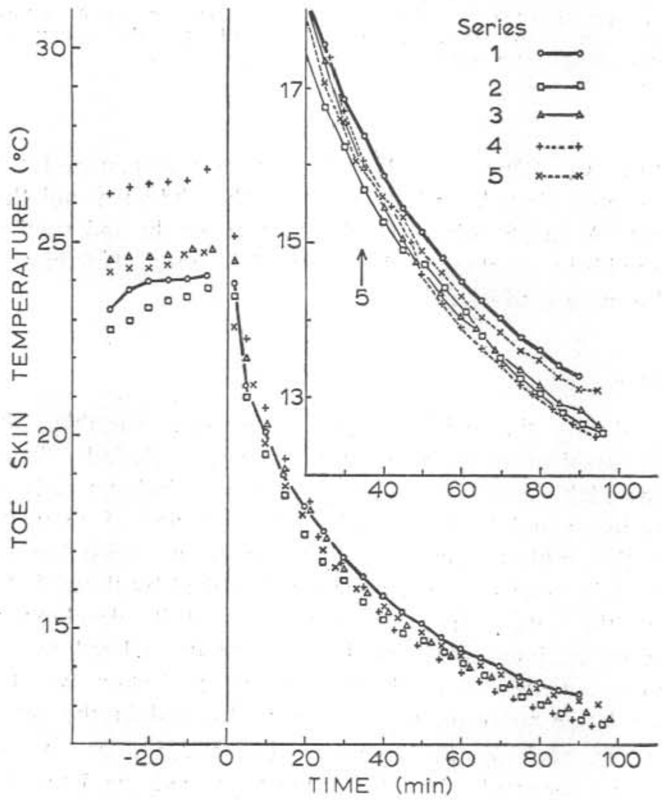

FIG. 21—Skin temperature of toe. Mean values (not adjusted by analysis of covariance) in each series. Zero time indicates the commencement of the cold phase. Inset, right-hand part of curves on a larger scale. The arrow indicates the inflexion in the curve in Series 5 which is referred to in the text.

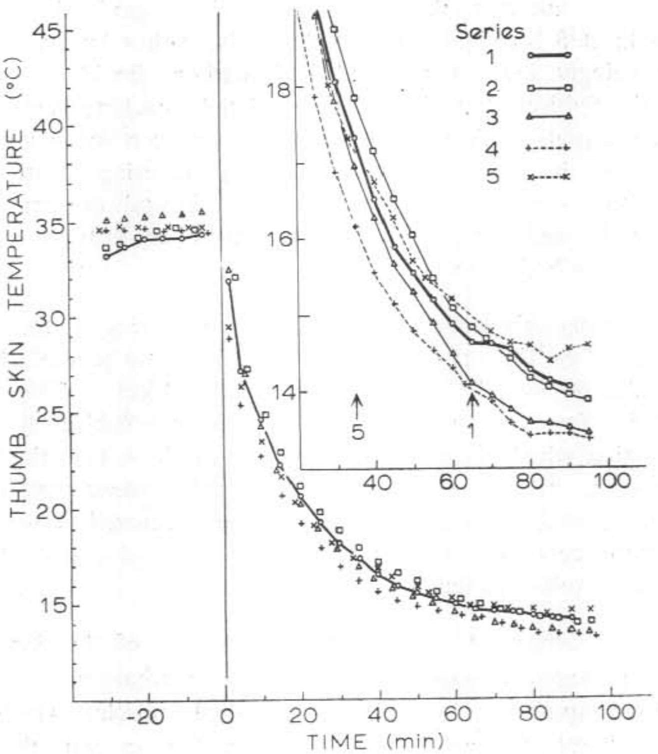

FIG. 22—Skin temperature of thumb. Mean values in each series. Zero time indicates the commencement of the cold phase. Inset, right-hand part of curves on a larger scale. The arrows indicate the inflexions in the curves in Series 1 and Series 5 which are referred to in the text.

Differences between series. The time after the onset of the cold exposure at which the first sign of shivering was observed is set out in Table 7. No consistent delay in the onset of shivering was apparent. In some of the exposures at Mawson, however, the initial period of shivering soon subsided and was followed by either quiescence or very limited activity for 10 to 30 minutes; Subject S showed this pattern in Series 2, 3 and 4, and Subject M in Series 2, the shivering activity being reflected in the values for oxygen consumption (Fig. 18). Subject A, however, showed no consistent variation between series, and Subject B's shivering changed only in quality. Subject A's anomalous response in Series 5 was characterised by an earlier onset and more rapid progression of shivering than occurred in its replicate.

Differences between subjects. Systematic differences between subjects were apparent, which did not seem to be related to body size or fatness. Subject B was the fattest subject, Subject M the heaviest, and Subject S the thinnest and lightest. Subjects A and B shivered vigorously early in the exposure and reached high levels of activity within the first 20 minutes, whereas Subjects M and S tended to increase their shivering activity gradually throughout the exposure. Subject S breathed slowly and quietly, with a low ventilation volume and correspondingly low oxygen and high carbon dioxide concentrations in the expired air; Subject B usually hyperventilated, reaching ventilation volumes of 22 litres per minute, with correspondingly high oxygen and low carbon dioxide concentrations in the expired air. Subject S's shivering mostly consisted of a continuous fine, rapid fibrillation with little skeletal movement; Subject B shivered violently and after Series 1 developed an entirely new mode of shivering, as described below.

The undulatory shivering of Subject B. In Series 1 the only skeletal movement caused by the shivering of Subject B was a general shaking of the trunk and limbs, as was the case with the other subjects. Fifty minutes after the onset of his first exposure in Series 2, however, Subject B developed an undulatory motion which thereafter occurred (in addition to orthodox shivering) in every exposure. It consisted of a lateral wriggling movement of head, trunk and legs; rolling and bouncing movements also occurred, possibly owing to the elastic resonance of the nylon-net mattress. The subject insisted that these movements were quite involuntary.

Although no other subject exhibited movements of this kind, Subject M (in Series 3) provided a possible clue to their mechanism when he showed occasional tonic spasms of unilateral abdominal muscles which caused his hips to swing sharply to one side. This observation suggests that Subject B's movements may have been due to rhythmic tonic contractions of unilateral muscle groups, alternating between the two sides of the body. The significance of this change in the manner of shivering is obscure.

Table 7.—Time (min) from commencement of cold exposure to the onset of shivering.

Subject and replicate	Series 1	2	3	4	5	*Mean*
A	4	3	3	6	2	4.0
A2	<5	4	5	3	5	
B	9	9*	6	<5	11*	7.3
B2	5	5	6	<6	11*	
M	<7	10*	5	5	6	6.3
M2	5	10*	5	5	5	
S	7	2	3	6	3	9.2
S2	8	31*	4	27*	1	
Mean	6.2	9.2	4.6	7.9	5.5	

* The first sample of expired air was collected before shivering was observed.

Despite the considerable bodily activity caused by these movements, Subject B's oxygen consumption was no higher in Series 2 than in Series 1, and in subsequent series it progressively declined (Fig. 13). Air movement over his skin, however, must have been greatly increased as a result of these movements.

Heart rate

The mean heart rate for each 5 minutes of the cold exposures in Series 3, 4 and 5, and the mean heart rate during each determination of oxygen consumption, are shown in Fig. 23. On the average, heart rate during the cold exposure increased by some five beats per minute over the warm-phase values, in a pattern rather similar to that of oxygen consumption; this similarity was noted previously by Adolph & Molnar (74). However, Tables A24-A26, which present the means of all values recorded for each subject in the warm and cold phase of each series, show that the average pattern of response seen in Fig. 23 does not reflect the response of all subjects, for the heart rates of Subjects M and S generally slowed during the cold exposure. No consistent variation between series was apparent, either in the warm phase, the cold phase, or the difference between them.

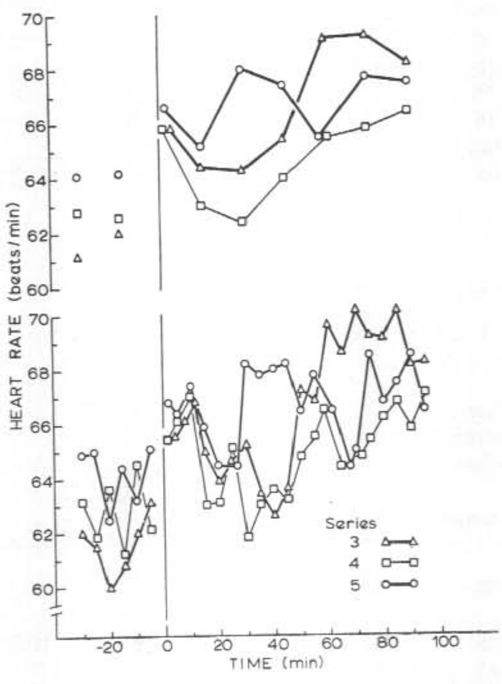

FIG. 23—Heart rate in Series 3, 4 and 5. Mean values in each series. Zero time indicates the commencement of the cold phase. The upper portion of the figure shows the average heart rate during each determination of oxygen consumption, plotted against the time of commencement of the determination.

Cold diuresis

The results of some of the urine collections in Series 4 and 5 are set out in Tables 8 and 9. The tables require little comment. The flow rates are comparable with those observed by Adolph & Molnar (74) and by Bader, Eliot & Bass (75). The flow rate of 300 ml/hr observed in the warm phase in Subject S, Series 5 (first exposure), is hard to explain, as his only fluid intake since awakening had been half a cup of coffee and the milk on his cereal, four hours before the beginning of the cold exposure. A similar high flow rate of 250 ml/hr in the warm phase which occurred in Subject A, Series 5 (first exposure), may have represented diuresis due to two cups of tea drunk 3½ hours before the cold exposure commenced.

Table 8.—Examples of urine flow rates in Series 4.

Subject	*Time (min) from onset of cold exposure*	*Time (min) since last urination*	*Volume* (ml)	*Urine flow since last urination* ml/hr	ml/min
S	84	41			
	110	26	140	325	5.4
S*	−52		120		
	58	110	430	235	3.9
	110	52	270	310	5.2
A*	55		665		
	110	55	415	455	7.6
B	−160				
	105	265	1200	270	4.5

* Second replicate.

Table 9.—Urine flow rates of Subject S in Series 5.

Replicate	*Time (min) from onset of cold exposure*	*Time (min) since last urination*	*Volume* (ml)	*Urine flow since last urination* ml/hr	ml/min	*Specific gravity*	*Remarks*
1	−75						
	−17	58	300	300	5.0		Warm phase.
2	−150						
	−35	115	143	75	1.2	1.022	Warm phase. Colour dark.
	27	62	350	340	5.7	1.006	Colour very pale.
	72	45	310	415	6.9	1.006	
	100	28	74	160	2.7	1.014	
	165	65	50	45	0.8	1.020	Colour darker.

The occurrence of these high flow rates in the warm phase makes it hazardous to assume that in the case of Subject S, Series 5 (second exposure), the flow continued at the observed rate of 75 ml/hr for the remaining 35 minutes of the warm phase. If, however, this assumption were to be made, and the appropriate correction (44 ml) subtracted from the first urine volume measured in the cold phase, the result of the calculations would indicate the extremely high flow rate of 680 ml/hr (11.3 ml/min) in the first 27 minutes of the cold exposure, with a specific gravity of 1.004. No explanation is suggested for the occurrence of more marked cold diuresis on these few occasions in Series 4 and 5 than in earlier series.

Subjective impressions

The subjects considered the test cold exposures to be equally unpleasant in all series, but the second replicate generally seemed a little easier than its predecessor. Thermal sensation of the trunk, hands and feet at the end of the exposure was much the same in Series 3, 4 and 5; it was not investigated in Series 1 and 2. The extremities were often painfully cold or numb by the end of the exposure.

DISCUSSION

Differences between subjects

Highly significant differences between the subjects of this study were noted in the warm-phase values for rectal temperature, oxygen consumption and thigh skin temperature, and in all responses to the test cold exposure except toe skin temperature.

Such differences, which are a commonplace of all biological experimentation, can sometimes be related to certain physical characteristics of the subjects, but often no satisfactory explanation can be found. In the present instance, correlation coefficients calculated from pairs of observations made on only four subjects would be of very doubtful value, so instead the body weight, surface area, skinfold thickness and physiological responses of the subjects have been ranked in order of magnitude (Table A21), so that correlations may be seen at a glance.

Only the values for rectal temperature and thigh skin temperature in the cold phase show clear correlations, and these are not with skinfold thickness, as might have been expected from the work of Baker & Daniels (76), but with body weight and surface area. Oxygen consumption, moreover, does not correlate well with body weight or surface area in either the warm phase or the cold phase. These unexpected effects presumably are due to the small number of subjects. Each of the variables listed reflects part of a complex and integrated response, the details of which vary between individuals. In a sample as small as the present one, individual variations may be expected to obscure the correlations that might be found if an adequate sample were to be studied.

Warm-phase results

The variation between series in rectal temperature and thigh skin temperature was statistically significant, but no clear relation to any known environmental variable was apparent, and no explanation is suggested.

The range of variation between series means is small (Table A2) — 0.2°C for rectal temperature, 2 kcal/m^2/hr for metabolic rate, 1.5°C for all skin temperatures except that of the toe — indicating that the thermal and metabolic state of the subjects immediately before the test cold exposure was similar in each series. The absolute values indicate that the subjects were warm and that their metabolic rates were close to basal values (77).

The present findings may be compared with those of several previous studies. Changes in deep body temperature, associated with the seasonal changes in environmental temperature, have been observed by Driver (78) and Palmai (79). Massey (80) and Lewis (81), however, have not observed any consistent seasonal pattern, and the present study supports their findings.

Seasonal changes in the basal metabolic rate of men living in cold climates have been reported by Butson (41), Wilson (82), and Van der Merwe & Holemans (83), but were not observed by Lewis, Masterton & Rosenbaum (22), nor by Milan, Elsner & Rodahl (15). The warm-phase metabolic rates in the present investigation, although not basal, may be regarded as supporting the findings of the last two groups of authors, for no seasonal variation was apparent.

An increase in physical fitness has been reported to produce higher skin temperatures (39, 55). In the present study, significant variation in skin temperature between series (in the warm phase) occurred only in the case of the thigh, and this variation correlates neither with the subjects' main periods of physical exertion nor with their subjective estimates of physical fitness. Detailed comparison of the variations in physical fitness (Fig. 8) with the variations in skin temperature at the other sites (Fig. 11) confirms this finding, leading to the conclusion that the changing levels of physical fitness during the present study failed to produce recognizable changes in skin temperature.

Cold-phase results

The main finding of this study was that the ability to maintain rectal temperature under acute cold stress improved in the Antarctic. The difference between Series 3 and Series 5 is striking. After 95 minutes of exposure to cold the rectal temperature of the subjects in Series 3 was either steady or falling slowly, and was still close to, or even above, pre-exposure values, whereas in Series 5 it was as much as 1.0°C (1.8°F) below pre-exposure values and was falling steeply. This difference between Series 3 and Series 5 is qualitatively similar to that observed for colonic temperature between cold-acclimatized and unacclimatized rats and rabbits (84) (Fig. 24) — even though, as will be seen, the mechanism is different.

Acclimatization to cold suggests itself as the obvious explanation, but such a conclusion requires critical examination before it can be accepted. Bass & Henschel (85) have drawn attention to some of the difficulties in the interpretation of seasonal changes, and have noted some of the confounding variables that may be present. In the present study it has been seen that the changes in rectal temperature response were not related to changes in the test cold stress, mean radiant temperature, relative humidity, body weight or surface area. Increased physical fitness has not been observed to improve the ability to maintain rectal temperature during acute cold stress (27, 39, 55), nor do the variations in physical fitness during the present study correlate with the variations in rectal temperature response.

Animals are considered to have acclimatized to cold if they undergo "measurable physiological changes that make them more successful in withstanding cold stress" (86). The enhanced ability to maintain rectal temperature that was found in the present study appears to satisfy this definition, and it seems safe to conclude that these changes represent the development and later decay of general acclimatization to cold. Because it is by far the most consistent finding of this study, rectal temperature response alone will be used as an index of acclimatization (as it often is in animal work) in the following section. The observed changes in other variables will be considered in a later section dealing with the mechanism of acclimatization.

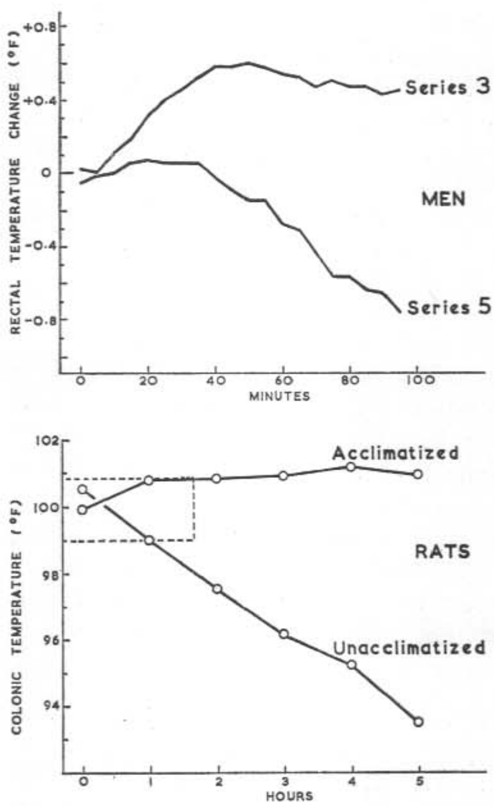

FIG. 24—The responses to cold of men at Mawson (Series 3) and Melbourne (Series 5) compared with those of cold-acclimatized and unacclimatized rats. Note the difference in scale in the two diagrams: the area enclosed by the broken lines in the "rats" diagram is equivalent to the area of the "men" diagram. The diagram illustrating the changes in rats is reproduced by kind permission of the editor of *Cold Injury* (84).

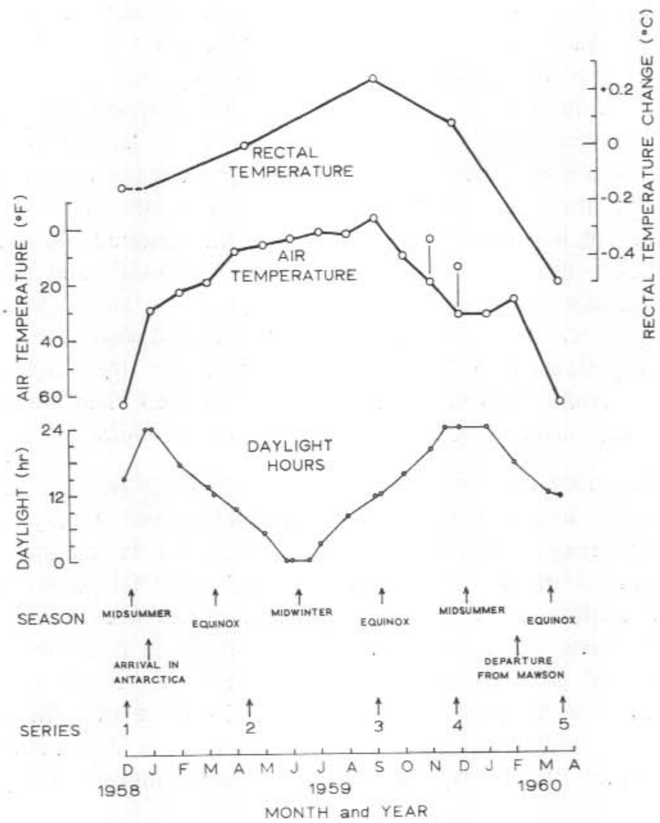

FIG. 25—Acclimatization in relation to air temperature, hours of daylight, and the season of the year. The curve for air temperature has been inverted; the additional values plotted for November and December are the temperatures experienced inland by Subjects A, B and S. The hours of daylight are those between sunrise and sunset, taken from current astronomical tables.

Climatic stress and acclimatization

Human acclimatization to heat has been studied in relation to the severity of the acclimatizing stress and the duration of exposure to it. It has been found that acclimatization to heat develops rapidly and is well marked in four to seven days (5), that its degree is dependent upon the level of the environmental heat stress (7), and that much of it is lost within a few weeks of cessation of exposure to heat (8). In animals artificially acclimatized to cold it has been found that the degree of acclimatization depends upon the level of cold stress to which they are exposed (87), and that acclimatization apparently decays more rapidly than it develops (88).

In a seasonal study of natural acclimatization to cold such as the present one, it is not possible to separate the two factors of the level of cold stress and the duration of exposure. Neverthless, it is of interest to examine the relation between the findings for rectal temperature and the changing levels of cold stress. Such an examination is facilitated by the relative constancy throughout the year of the time spent outdoors by the subjects, the clothing worn, and the wind speed. The main variables determining cold stress are thus air temperature and solar radiation (which is related to the seasonal changes in the hours of daylight), and in Fig. 25 these are plotted against rectal temperature response, here used as an index of acclimatization. The curve for air temperature has been inverted, it has been assumed that acclimatization did not commence until the subjects arrived in Antarctica, and the mean value for rectal temperature in Series 5 has been adjusted so as to exclude the effect of Subject A's anomalous response in one exposure of that series. The colder temperatures experienced in November and December by Subjects A and B, and to a lesser extent Subject S, in the course of their field work, are plotted in addition to the mean values recorded at Mawson station.

It is evident that acclimatization was not related to the season of the year, as it presumably would have been if an endogenous bodily rhythm were responsible, for Series 1 and 4 were both carried out in summer (December) and Series 2 and 5 in autumn (April). It was also not related to the hours of daylight, in contrast to seasonal changes in the heat tolerance of cattle (89). On the other hand, there appears to have been a clear relation between acclimatization and air temperature. Support for this conclusion is provided by the behaviour of Subjects A and B in Series 4, in that the high level of acclimatization to cold manifested by these subjects on that occasion followed closely upon their recent exposures to low temperatures during field work inland.

Development of acclimatization. The results of Series 2 indicate that some degree of acclimatization can develop in 15 weeks of residence in the conditions of cold encountered in this study. The degree of acclimatization, however, was small in comparison with that observed later in Series 3, and it is interesting to speculate whether the degree seen in Series 2 represents full acclimatization to the current (or recent) temperatures, or only partial acclimatization owing to insufficient time having elapsed for the development of full acclimatization. No firm conclusions can be drawn, but the latter possibility is favoured by the fact that between Series 1 and Series 2 the rectal temperature response improved by 0.15°C whilst the air temperature fell by 55°F (from 63°F to 8°F), whereas between Series 2 and Series 3 the rectal temperature response improved by a further 0.24°C whilst the air temperature fell by only 12°F. In other words, of the total improvement in the ability to maintain rectal temperature which developed over a period of 35 weeks in Antarctica, only 38% developed in the first 15 weeks even though 82% of the total fall in air temperature occurred in this period.

The lack of solar radiation between Series 2 and Series 3 would accentuate the effects of the fall in air temperature during that period, but the contrast is nevertheless suggestive. A time-lag of several months in the development of acclimatization would go far towards explaining the failure of most attempts to artificially acclimatize men to cold, for few experiments have continued so long. However, if this suggestion is correct then it becomes necessary to postulate that the lag between environmental change and physiological response does not remain constant as acclimatization proceeds, for in Series 4 Subjects A and B apparently responded to cold exposure sustained within the previous month.

Decay of acclimatization. The results of Series 5 indicate that acclimatization had almost completely disappeared 6 weeks after the subjects had left Mawson. A slight early rise in rectal temperature (or a delay in the onset of the fall) was the only sign of it remaining, and the rate of the subsequent fall was such that the subjects were less able to maintain their rectal temperature after 45 minutes of cold exposure than they had been before leaving Australia 17 months previously. This response was present in the first three subjects tested, 5 to 7 weeks after leaving Mawson, and also in the last subject, tested 10 weeks after leaving Mawson — a finding which is consistent with the concept that the decay of acclimatization in man occurs in an exponential fashion, as it does in animals (88).

The mechanism of acclimatization

The most striking feature of this study is the contrast between the consistency of the results for rectal temperature and the heterogeneity of those for all other variables, suggesting that the mechanism of the changes in rectal temperature is not likely to be an obvious one.

An improvement in men's ability to maintain rectal temperature under a standard cold stress could be brought about by one or more of the mechanisms set out below:

1. Metabolic acclimatization — in which there is a simple increase in heat production.
2. Changes in the distribution of body heat — in which rectal temperature is maintained by allowing a greater mass of peripheral tissue to cool, the rate of heat loss to the environment remaining unchanged.
3. Insulative acclimatization — in which there is a reduction in the rate of heat loss.

These possibilities will now be considered.

Metabolic acclimatization

Small animals acclimatized to cold in the laboratory have a raised metabolic rate at neutral temperatures, and they respond to cold exposure with a prompt, high and sustained further increase; as a result of this increased heat production colonic temperature is maintained at normal levels and the incidence of cold injury is reduced (2, 90).

In the present study, the variations in oxygen consumption appear to have been quite unrelated to the variations in rectal temperature response. Oxygen consumption throughout the exposure was unrelated to the final rectal temperature (Fig. 13), an extreme example being the response of Subject S in Series 5, when his highest oxygen consumption of the whole study (437 ml/min) was associated with his greatest fall in rectal temperature (—0.9°C). No early elevation of oxygen consumption occurred to account for the early rise in rectal temperature observed in the acclimatized state (Fig. 14 and 17); on the contrary, oxygen consumption in the acclimatized subject generally remained at lower levels than in the unacclimatized for the first half-hour of the cold exposure, during which period rectal temperature was nevertheless rising steeply. The increased oxygen consumption occasionally noted before shivering had commenced is not regarded as evidence of "non-shivering thermogenesis"; subjective impressions support the view of Swift (71) and others that it was due to increased muscular tone associated with exposure to cold.

Hart (2, 3, 91) has drawn attention to the differences between artificial and natural acclimatization in animals. In the laboratory the animals are conditioned to the single unchanging stimulus of low air temperature, whereas in the natural state they are exposed not only to fluctuating temperatures but to diurnal and seasonal changes in many other stimuli, such as daylight. Laboratory acclimatization is mediated by increased heat production, but natural acclimatization (especially in the larger animals) is mainly a matter of increased insulation, with little or no change in heat production — a much more practical response for animals that often are faced with scarcity of food in winter. Since the acclimatization observed in this study developed under natural conditions, it is perhaps not surprising to find that it was not mediated by increased heat production.

Changes in heat distribution

The differences between series in rectal temperature at the end of the cold exposure appear to indicate differences in body heat content (skin temperature remaining constant), and to show that the acclimatized subject incurred a smaller heat debt than the unacclimatized. An alternative hypothesis, however, must be considered: that the differences in rectal temperature reflect differences not in the heat content of the body but merely in its distribution.

Carlson, Young, Burns & Quinton (92) have suggested that the acclimatized man maintains a constant temperature of the deep body tissues (the "core"), and warmer extremity temperatures than the unacclimatized, by allowing a greater mass of peripheral tissue (the "shell") to cool. The lower heat production of the acclimatized man, in the presence of an unchanged rate of heat loss to the environment, results in a greater heat debt in the acclimatized than in the unacclimatized.

In the case of the present study, the hypothesis to be considered is that the higher rectal temperature in the acclimatized man was maintained at the expense of the body shell, the rate of heat loss to the environment remaining unchanged. Since heat production also remained virtually unchanged, heat debt would therefore have been the same in both the acclimatized and the unacclimatized.

This hypothesis can be tested by means of temperature measurements made after the vasoconstriction responsible for the altered distribution of heat had relaxed. Tables 10 and A27-A29 present the results of the temperature measurements made in the rewarming phase. The time since the end of the exposure was approximately one hour in all series except Series 1, so that differences in the time of rewarming are unlikely to have affected the results. Skin temperatures were higher than at the end of the cold exposure but were still well below pre-exposure values, and were similar in the four series in which they were measured. Rectal temperatures were lower than both the pre-exposure values and the values at the end of the cold exposure. The decrease in rectal temperature and the rise in skin temperature indicate that vasoconstriction had relaxed, both effects being due to the renewed flow of warm blood through cold peripheral tissues (93, 103). A marked variation between series in rectal temperature — and hence heat debt — was present, and it was of similar pattern to that present at the end of the cold exposure one hour earlier.

The rate of rewarming, although subject to random error, is considered to have been much the same in all the series, and unlikely to have itself

Table 10.—Rewarming-phase body temperature and time since end of cold exposure. Mean values of the eight observations for each series.

	Series 1	2	3	4	5
Time (min)	39	60	56	57	56
Rectal temperature change (°C) from warm-phase values	−0.47	−0.19	0	−0.27	−0.61
Skin temperature (°C)					
Abdomen	*	32.2	31.5	32.3	31.3
Thigh	*	29.6	29.4	28.6	29.7
Mean of abdomen and thigh	*	30.9	30.4	30.4	30.5

* Not observed.

produced the systematic variation in heat debt that was present after one hour's rewarming. It seems highly probable, therefore, that there were real differences between series in heat debt at the end of the cold exposure, of the kind suggested by the values for rectal temperature — that is, a smaller heat debt in the acclimatized than in the unacclimatized.

The alternative hypothesis is therefore unacceptable; the rectal temperature changes are unlikely to have been produced by changes in heat distribution alone — even though such changes may have occurred as part of some other mechanism of acclimatization. Since metabolic heat production remained virtually constant, it appears that the amount of heat lost during the cold exposure was less in the acclimatized than in the unacclimatized. It remains to be considered by what means such differences in heat loss — which imply greater insulation in the acclimatized — could have been produced.

Insulative acclimatization

Animals living in cold climates have been shown to differ from those in warm climates mainly in the extent of their insulation (94). In many of them the warm skin is insulated from the cold air by means of fur, but in "bare-skinned" animals, such as the seal (95, 96) and the Alaskan swine (97), insulation is provided by subcutaneous fat and by circulatory adjustments which allow the skin temperature to fall to a low level, reducing the temperature gradient from skin to air and hence reducing heat loss (98). Changes in insulation also appear to be the commonest means of seasonal acclimatization to cold in animals (3, 91, 96).

It is convenient at this point to summarise the results of some recent studies of human acclimatization to cold. Davis (16), studying subjects exposed to cold in a temperate climate and in the Arctic, observed a decrease in heat production and in shivering, with no consistent change in skin and rectal temperature. Milan and his co-workers (15), in their studies of seasonal changes in Antarctica, noted a decrease in heat production accompanied by increased skin temperature and unchanged rectal temperature. In the present study there was an increase in rectal temperature, no change in heat production, and no change in skin temperature other than a tendency to cooler extremities.

In each of these studies the subjects were exposed to a single level of air temperature in the test cold exposures. Wyndham & Plotkin (99) extended this work by exposing men in the Antarctic to a number of air temperatures, ranging from 27°C to 5°C. They found that exposure to an air temperature of 27°C evoked the same heat production as it had when the subjects were studied in South Africa before their departure for Antarctica, but that at all lower temperatures the heat production was less in Antarctica. Comparison of the regressions of heat production on air temperature for Antarctica and South Africa showed that the difference was not due to a change in elevation of the regression but rather to a change in its slope, both curves having a common origin at 27°C.

This change in slope of the regression of heat production on air temperature implies an increase in insulation, and is in fact the classic picture of "insulative acclimatization" as described by Hart (3) and previous authors. Wyndham & Plotkin's finding that these changes were associated with a decreased clothing requirement supports this conclusion, and suggests that similar observations on clothing by previous workers (40 to 43) did in fact indicate physiological acclimatization. Wyndham & Plotkin also confirmed Milan's findings that average skin temperature and extremity temperature were raised in the Antarctic and that rectal temperature was unchanged.

A common pattern is discernible in these four studies, if the results for skin temperature are for the moment ignored. A decrease in heat production with no change in rectal temperature (15, 16, 99), and an increase in rectal temperature with no change in heat production (the present study) each imply either a diminished heat loss or a greater heat debt. In the present study, at least, heat debt was reduced, and it is suggested that in all of these studies acclimatization resulted in an increase in over-all insulation.

The variability of the results for skin temperature might well have been due to differences in the physical fitness of the subjects. Chronic exposure to cold in the field is generally associated with strenuous exercise, which produces an improvement in physical fitness. Heberling & Adams (39) have shown that an increase in physical fitness alone can produce the raised skin temperatures often noted in field studies of acclimatization, and that subsequent exposure to cold produces little, if any, further change. Whether higher skin temperatures will be observed with acclimatization, therefore, might depend upon the subject's activity during acclimatization and on his initial state of physical fitness. In the present study no elevation of skin temperature was observed, even though changes in fitness evidently occurred (Fig. 8). It may be significant that the subjects were active men who habitually maintained a level of fitness that was above the general average; this initial high level of fitness might have modified the effects of the relative increase in fitness that occurred in the Antarctic.

The unbalanced heat equation. A feature common to all these studies is that the results for skin temperature appear to be inconsistent with those for heat production and rectal temperature, a paradox which Milan (15) has described as an "unbalanced heat equation." The changes in heat production and rectal temperature that suggest an increase in insulation also imply a decrease in skin temperature, but only in the present study was there any suggestion of this decrease, and even then it was largely confined to the extremities. In the other studies, skin temperature was either unchanged or increased.

This apparent failure of skin temperature to reflect changes in heat loss is a matter of considerable theoretical and practical importance. As long ago as 1918 (100) it was argued that skin temperature is not a reliable guide to heat loss from the body, since modifications of the internal gradients within the tissues might change heat loss without affecting the skin temperature. In 1934, however, Burton (101) concluded that this argument was fallacious, and outlined the theory of heat flow in the animal body which has since become widely accepted. Explanations of the paradoxical results for skin temperature mentioned above which are consistent with this theory have been suggested by several authors (15, 30, 102).

The studies in which these paradoxical results were obtained were all short exposures to fairly severe cold, in which thermal equilibrium was rarely, if ever, attained. They therefore fail to meet the fundamental requirement (thermal equilibrium) of the simplified theory of heat flow proposed by Burton, and it may be that the errors arising from this cause are sufficient to produce the observed effects. "Stored" heat from cooling superficial tissues, for instance, might well obscure the effect upon skin temperature of a reduced rate of heat flow from deeper tissues — particularly in the early part of the exposure.

Another possible cause of paradoxical results for skin temperature is that the areas sampled, or their weighted average, might not afford an accurate estimate of the average skin temperature of the whole body. This limitation certainly applies to the present study, but in at least some of the other studies in question the areas sampled were those generally considered to give a reasonable estimate of average skin temperature. Heberling & Adams (39), for instance, measured skin temperature at 16 sites, yet were forced to comment:

> "The maintenance of internal (rectal) temperatures in the face of the implied increased heat losses from the warmer extremities, with no compensation of increased heat production, presents a paradox for which we have no ready solution. It is reassuring to note that a similar dilemma is presented by data from an independent study . . ."

A third possibility is that for a given average skin temperature, heat loss might be changed by modifications in one or more of the other factors affecting heat exchange between the skin and the environment. It has been suggested, for instance (15, 30), that a reduction in shivering would reduce heat loss by convection, owing to the resultant decrease in air movement over the skin. This factor might be significant in cases where a decrease in shivering occurs, but decreased shivering was not reported in the three Antarctic studies in question, and in Subject B of the present study air movement was increased.

Other factors besides air movement, however, can affect heat loss from the skin. Convection is modified by the curvature of the surface, radiation is modified by the degree to which the skin is facing the environment rather than other areas of skin (as in the case of the medial thigh), and both these factors vary from place to place on the body surface. It is therefore conceivable that variations in the distribution of skin temperature could produce changes in heat loss from the body as a whole, even though average skin temperature were to remain unchanged. Counter-current heat exchanges in the limb vessels (103) may be suggested as one means by which such variations could be brought about.

Whatever the relative importance of each of these factors in the studies under consideration may have been, it is evident that there are grounds for caution in drawing conclusions about heat loss from the results of measurements of skin temperature during brief exposures to cold. Direct measurements of heat loss during acclimatization by means of gradient calorimetry, together with studies of the distribution of skin temperature, should prove useful in clarifying these questions.

In conclusion we may note an interesting example of an "unbalanced heat equation" in connection with seasonal changes in the harbour seal *Phoca vitulina concolor* (96). Deep body temperatures, skin temperatures and temperature gradients within the subcutaneous tissues were the same in summer and winter seals, yet the winter seals had a smaller metabolic response to cold and a greater over-all tissue insulation than the summer seals. The authors suggest that less heat may have been lost from the flippers in winter, as a result of variations in the activity of the heat-exchanger system common to many aquatic and terrestrial mammals (104, 105). In the present study, the colder toe temperatures observed in the Antarctic are suggestive; ambient temperatures during the test cold exposures being 10°C, the fall in toe temperature from Series 1 to Series 2 almost halved the skin-to-air temperature gradient.

Changes in tissue insulation. The changes in the insulation of the tissues which apparently were the basis of the acclimatization observed in this study could have been produced in two ways — by the deposition of fat and by changes in the circulation.

Baker & Daniels (76) have reported a positive correlation between body fatness and the ability to maintain rectal temperature in the cold. Although it is probable that Subject M's anomalous response in Series 1 (when he was 6 kg overweight) was due to his obesity at that time, the lack of correlation between the changes in each subject's body weight and rectal temperature response during the remainder of the study makes it extremely unlikely that changes in fatness were responsible for the improved ability to maintain rectal temperature, for fatness is generally highly correlated with body weight (106, 107). It remains to be considered whether changes in the circulation could have been responsible.

A paradoxical rise in rectal temperature on exposure to cold has been noted by many observers. It is generally explained as being due to the abrupt reduction in the volume of cool blood returning from the periphery, as a result of vasoconstriction. Aschoff (108) and Bazett *et al.* (103) present some striking examples of this phenomenon, in which the change in rectal temperature was brought about by the immersion of a single hand or arm in cold water. In Aschoff's example, rectal temperature rose as a result of generalised vasoconstriction of peripheral vessels when the hand was immersed in ice water, and subsequently fell as cold vasodilatation developed and the hand rewarmed.

Fig. 26, which shows some unusual fluctuations of thumb and rectal temperature that occurred during Subject S's first exposure in Series 4, appears to illustrate the same phenomenon, the lag of 5 to 10 minutes in rectal temperature possibly being due to faeces in the rectum. The magnitude of the changes in rectal temperature (0.5°C) suggests that the variations in thumb temperature were part of a widespread variation in vasomotor tone; the changes of up to 0.6°C observed in abdomen temperature, in phase with the changes in thumb temperature, may have been part of this, although thigh and toe temperatures seem to have been only slightly affected. If this explanation is correct, the decrease in the slope of the thumb cooling curve at 35 minutes indicates a relaxation of vasoconstriction which allowed more blood to circulate through chilled peripheral tissues and so cool the "core," whilst the steepening of the

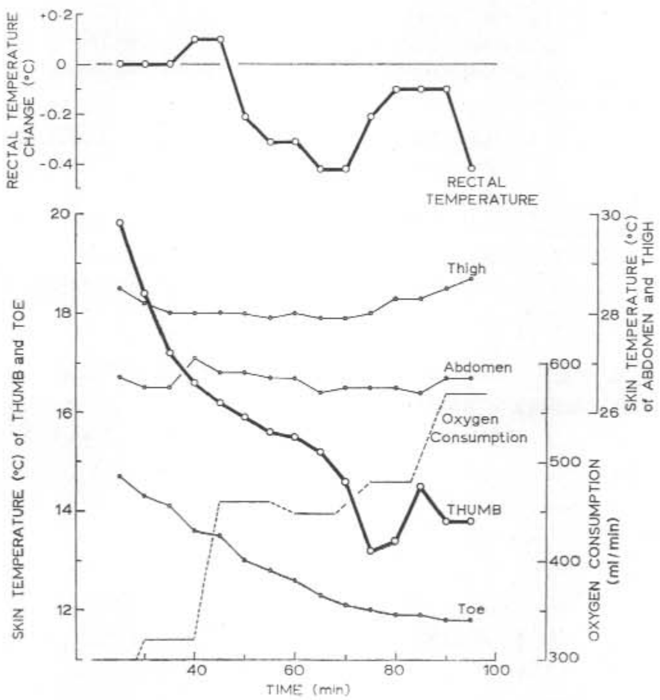

FIG. 26—Body temperature and oxygen consumption during part of the first exposure of Subject S in Series 4.

slope of thumb temperature at 60 minutes indicates an intensification of vasoconstriction which reduced the flow of cooled blood to the core and produced a rise in rectal temperature.

A similar relation between rectal temperature and extremity temperature is apparent in the mean values for each series (Fig. 14, 21 and 22). In Series 1 the secondary fall in rectal temperature commenced at 65 minutes; simultaneously there was an abrupt reduction in the rate of cooling of the thumb. In Series 5 rectal temperature began to fall steeply at 35 minutes, and simultaneously there were reductions in the rate of cooling of both thumb and toe. These inflexions in the cooling curves of toe and thumb in Series 1 and 5 served to change the position of these curves relative to those for Series 2, 3 and 4, which continued falling, at a fairly steady rate, to lower temperatures than in Series 1 and 5.

On the basis of these observations, it is suggested that the early rise in rectal temperature in the acclimatized subject indicates a more prompt, intense and sustained peripheral vasoconstriction (possibly more widespread in area and in depth) than in the unacclimatized. Its promptness avoids the loss of heat from the body core which would otherwise occur in the period between the onset of cold exposure and the establishment of effective vasoconstriction; and its intensity and extent reduce the rate of heat loss from the body core as skin temperature falls to values near equilibrium with the environment, because of the increased insulation they provide. Heat production being similar in the acclimatized and the unacclimatized, the relative effectiveness of the insulation provided by the vasoconstricted tissues in each case is reflected in the slope of the later fall of rectal temperature, which is least steep when the subjects are most acclimatized (Fig. 14). Men who have almost lost their acclimatization (Series 5) respond with an initial vasoconstriction which is weaker than that of acclimatized men, although stronger than that of unacclimatized men, but are unable to sustain it. The vasoconstriction soon relaxes, allowing warm blood to circulate more freely through the chilled peripheral tissues, with the result that the rate of fall of skin temperature decreases and rectal temperature falls steeply.

A good illustration of this hypothesis as it relates to the development of acclimatization is provided by Fig. 27. When acclimatized, the subject showed a prompt rise in rectal temperature, the lower skin temperatures to be expected from intensified vasoconstriction, and a very late response of shivering and increased heat production (Table A23). Such a clear pattern, however, was rarely seen, particularly as regards skin temperature, and surface indications of vasomotor changes were usually limited to small, although definite, changes of slope in the cooling curves of the extremities. The reason for this lack of consistency presumably lies in the inadequacy of the few skin temperature sites sampled to indicate either the spatial distribution of the vasoconstriction or its effects upon counter-current heat exchanges.

The response of men who have almost lost their acclimatization, as seen in Series 5, has some interesting implications (Fig. 14). The difference between the initial response in Series 5 and in the "acclimatized" series appears to have been merely one of degree, yet after the first 45 minutes of cold exposure the partially acclimatized subjects in Series 5 were even less successful in maintaining their rectal temperature than were the unacclimatized subjects in Series 1. This raises the question whether a similar fate, presumably due to a failure of vasoconstriction, awaits the more acclimatized subject after a certain period of time. In prolonged cold exposure, over a period of several hours or longer, would the acclimatized subject maintain his superiority over the unacclimatized? Or does each degree of acclimatization have a time-limit, beyond which it changes, as in Series 5, from being an advantage to being a disadvantage? If such a time-limit exists, what is its relation to the degree of cold stress? Is it shorter in a more severe exposure?

These and many other such questions await further investigation. Whatever the value of the cold acclimatization seen in this study may have been in other conditions of cold stress and exposure time, we may note how very appropriate this enhanced vasoconstriction was to the conditions under which it developed — in which one of the main experiences of cold was that of

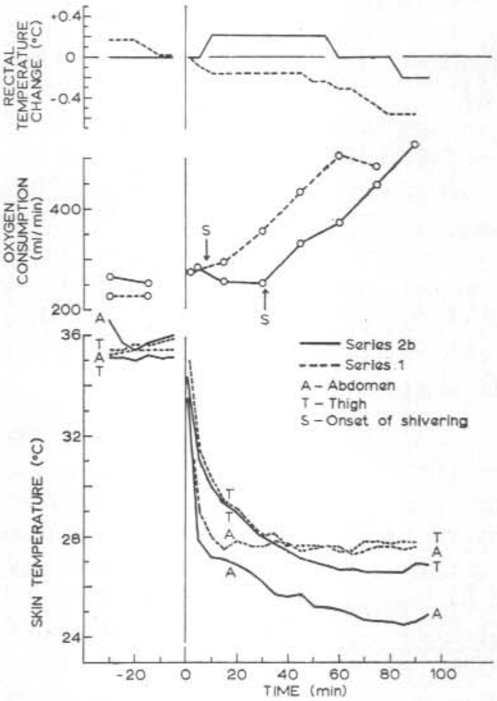

FIG. 27—Body temperature, oxygen consumption and onset of shivering of Subject S in the second exposure of Series 2, compared with his mean values in Series 1. Zero time indicates the commencement of the cold phase.

superficial chilling of brief duration, repeated more than a score of times on every day that the subjects were at Mawson station.

Catecholamines and acclimatization

The anomalous response of rectal temperature in Subject A's first exposure (5a) in Series 5 was similar to his "acclimatized" response in Series 3, whereas in his second exposure (5b) it was typical of Series 5. It is interesting to compare these two exposures, and to contrast them with the mean values for this subject in Series 1 and Series 3 (Table 11, Fig. 16). In exposure 5a the rectal temperature at 90 minutes was 1.00°C higher than in Exposure 5b, skin temperatures were between 0.8°C and 1.4°C higher, and the subject felt warmer than in any other exposure of the whole study. Heat production in Exposure 5a was 17 kcal/m^2/hr greater than in Exposure 5b, an increase of 23%. Exposure 5a, therefore, would seem to be a clear example of "metabolic acclimatization".

This explanation, however, requires qualification. Heat production in Series 1 was fully as high as in Exposure 5a, yet rectal temperature was not maintained at the pre-exposure level; and in Series 3 the rectal temperature was excellently maintained in spite of heat production being nearer to that of Exposure 5b than that of Exposure 5a. Subject A's anomalous response was evidently mediated by something else besides increased heat production. The most likely explanation is that the efficiency of his residual insulative acclimatization was increased by some factor which enabled him to take full advantage of the high level of heat production, itself possibly caused by the same factor.

The factor producing this effect was apparently related to lack of sleep, for the only unusual circumstance about Exposure 5a was that the subject had not gone to bed until 4 a.m. on the morning of the cold exposure; he had not

Table 11.—Body temperature and heat production of Subject A in the two replicate exposures of Series 5, compared with his mean values in Series 1 and Series 3.

	Series 1 mean	*Series 3 mean*	*Series 5 Exposure a*	*Series 5 Exposure b*
Rectal temperature change (°C)	−0.25	0.16	0.22	−0.78
Oxygen consumption (ml/min)	542	479	549	445
Heat production (kcal/m^2/hr)	88.2	76.2	88.3	71.6
Skin temperature (°C)				
Abdomen*	27.7	27.0	28.5	27.1
Thigh	25.2	26.6	27.3	26.2
Toe*	13.6	12.9	13.0	12.0
Thumb	14.0	14.3	13.9	13.1

* Adjusted values.

consumed an excessive amount of alcohol the previous evening. He had risen at 8 a.m., after less than four hours' sleep, to come to the laboratory, and had remained awake during the experiment.

Men exposed to cold (109) or doing light work of a grade equivalent to that done by Subject A in shivering (110) have been shown to excrete in the urine a greater amount of the catecholamines adrenaline and noradrenaline than resting men. The rate of excretion associated with light work is greatly increased if the men are suffering from lack of sleep, and this increase is greater in cool than in warm environments (110). In view of these findings, it seems likely that Subject A's anomalous response in Series 5 was accompanied by an abnormally high urinary excretion of adrenaline and noradrenaline as a result of lack of sleep, and that a change in the secretion or utilization of these hormones was responsible for the changes in insulation and heat production in this exposure (111).

Catecholamines have been shown to play an important part in acclimatization to cold in animals (112, 113). The similarity of Subject A's responses in Exposure 5a and the previous "acclimatized" exposures raises the question whether a change in catecholamine secretion or utilization might have been concerned in the latter exposures also. No direct evidence is available, but the behaviour of Subject A's heart rate may be relevant, for it was similar in Exposure 5a and the "acclimatized" exposures, in both the warm phase and the cold phase (Table 12, Fig. 16). The heart rate in Exposure 5b contrasted sharply by being higher in the warm phase and lower in the cold phase, so that instead of a tachycardia of 11 beats per minute during the cold phase there was a bradycardia of 2 beats per minute — in keeping with the results of a previous study on unacclimatized men (109). The consistency of heart rate shown by Subject A, however, was not seen in the heart rates of the other subjects, so that no general conclusions can be drawn.

The peripheral vessels of artificially acclimatized small animals show a diminished response to catecholamines, probably because of a decrease in sensitivity (114). If this is an adaptation to the elevated blood levels of catecholamines associated with the increased heat production, then in man the response of the peripheral vessels might well be different, for heat production is not increased. Reports of increased sensitivity to adrenaline in men living in Antarctica (40, 41) lend interest to this possibility.

Table 12.—Heart rate (beats/min) of Subject A in Series 3, 4 and 5.

	Series 3		*Series 4*		*Series 5*	
	Exposure a	*Exposure b*	*Exposure a*	*Exposure b*	*Exposure a*	*Exposure b*
Warm phase	64	66	66	66	66	71
Cold phase	79	75	76	75	79	69
Difference	15	9	10	9	13	−2

SUMMARY AND CONCLUSIONS

In this study the responses of four caucasian men to acute cold stress were tested in Australia and Antarctica on five occasions over a period of 73 weeks. During this time the climatic conditions to which they were exposed underwent a single oscillation of wide amplitude, the average monthly air temperature ranging from 63°F to —4°F and back again and the average wind speed mostly remaining over 20 m.p.h. On every day of the 57 weeks that the subjects were in Antarctica they were briefly exposed to the outdoor environment more than a score of times, usually inadequately dressed. In addition they habitually spent much of their working time outdoors.

The principal finding was that in Antarctica a highly significant improvement occurred in the men's ability to maintain rectal temperature during acute cold stress. This change is attributed to general acclimatization to cold. Heat production and skin temperatures did not change significantly, but extremity temperatures during the cold exposure were generally lower in Antarctica than in Australia. There were highly significant systematic differences between subjects.

The increased insulation implied by these findings (and by those of three other studies cited) is not attributable, in the present case at least, to changes in fatness or in shivering. Evidence suggesting that the insulation of the tissues was increased as a result of enhanced vasoconstriction is provided by certain synchronous variations that occurred in rectal temperature and extremity temperatures. There is some evidence to suggest that a change in the secretion or utilization of catecholamines may have been involved in this process.

The degree of acclimatization was inversely related to the outdoor air temperature, but not to the hours of daylight or the season of the year. After 15 weeks of residence in Antarctica, when four-fifths of the total change in air temperature had already occurred, the degree of acclimatization was only one-third of the maximum that was observed after 35 weeks in Antarctica, suggesting that acclimatization may be slow to develop. The rate of decay was rapid, for acclimatization had almost completely disappeared 6 weeks after cold exposure had ceased. The small degree of acclimatization that remained had the paradoxical effect of rendering the subjects less able to maintain their rectal temperature than they had been before acclimatization was first achieved.

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APPENDIX

Table A1.—Climatic conditions at Mawson, 1959-1960. Data taken from published meteorological records (50, 51).

Month and year	Monthly mean	Temperature (°F) Maximum Highest	Maximum Mean	Minimum Lowest	Minimum Mean	Windspeed (m.p.h.) Monthly mean	Windspeed Max. gust	Sunshine (hr) Daily mean
1959								
January	29.3	39.8	32.9	17.6	24.9	20.4	75	7.3
February	22.3	37.4	27.6	7.5	16.9	19.3	76	9.5
March	19.5	33.1	23.2	3.9	15.3	26.8	115	3.7
April	8.1	31.5	13.0	−10.3	3.5	19.1	83	4.7
May	6.1	26.5	11.5	−13.4	0.6	23.3	84	2.0
June	3.8	21.6	9.0	−13.6	−0.9	20.2	77	0.1
July	1.1	19.6	5.5	−19.0	−3.3	26.7	124	0.6
August	2.0	25.8	6.5	−19.5	−2.5	24.0	105	3.0
September	−3.6	21.1	0.9	−28.2	−9.0	27.8	107	3.4
October	10.1	25.4	15.0	−7.0	4.2	20.4	102	7.7
November	19.5	30.5	25.0	6.5	13.4	17.8	74	8.7
December	31.4	42.1	36.0	19.9	26.8	19.1	86	8.2
Mean	12.5		17.2		7.5	22.1		4.9
1960								
January	31.5	42.1	35.8	21.3	27.1	17.3	79	8.3
February	26.0	43.3	31.6	5.0	20.4	20.5	81	7.7

Table A2.—Warm-phase body temperature and oxygen consumption. Mean values of the eight observations for each series.

	Series 1	2	3	4	5
Rectal temperature* (°C)	36.67	36.80	36.76	36.59	36.79
Oxygen consumption (ml/min)	267	256	265	251	265
Metabolic rate† (kcal/m²/hr)	41.5	40.0	41.2	39.6	41.2
Skin temperature (°C)					
Abdomen	35.2	34.8	35.2	35.0	35.1
Thigh*	34.8	34.5	34.8	34.1	34.0
Toe	24.1	23.8	24.8	26.9	24.8
Thumb	34.3	34.6	35.5	34.5	34.7

* Differences between series means significant at 5% level. Significant differences for comparing means (5% level):

Rectal temperature: 0.13°C.

Thigh skin temperature: 0.7°C.

† Obtained by simple conversion from the mean values for oxygen consumption. A separate analysis of variance for metabolic rate was not done.

Table A3.—Warm-phase rectal temperature (°C). Each value is the mean of the two replicates.

Subject	Series 1	2	3	4	5	Mean
A	36.67	36.74	36.64	36.39	36.69	36.63
B	36.50	36.60	36.64	36.39	36.68	36.56
M	36.67	36.92	36.85	36.80	37.08	36.87
S	36.83	36.92	36.90	36.76	36.71	36.82
Mean	36.67	36.80	36.76	36.59	36.79	

Table A4.—Warm-phase oxygen consumption (ml/min). Each value is the mean of the two replicates.

Subject	Series 1	2	3	4	5	Mean
A	270	259	272	276	276	271
B	254	248	256	226	258	249
M	315	262	291	272	303	288
S	229	254	242	231	222	236
Mean	267	256	265	251	265	

Table A5.—Warm-phase abdomen skin temperature (°C). Each value is the mean of the two replicates.

Subject	Series 1	2	3	4	5	Mean
A	35.2	33.9	35.1	34.2	35.4	34.8
B	35.3	34.8	35.0	35.0	34.2	34.9
M	35.1	34.8	34.8	35.6	35.1	35.1
S	35.4	35.6	35.8	35.4	35.6	35.5
Mean	35.2	34.8	35.2	35.0	35.1	

Table A6.—Warm-phase thigh skin temperature (°C). Each value is the mean of the two replicates.

Subject	Series 1	2	3	4	5	Mean
A	34.2	34.1	34.6	33.8	34.0	34.1
B	34.1	34.0	34.2	32.8	32.8	33.6
M	35.3	34.8	35.0	34.9	34.2	34.9
S	35.8	35.0	35.5	34.8	34.9	35.2
Mean	34.8	34.5	34.8	34.1	34.0	

Table A7.—Warm-phase toe skin temperature (°C). Each value is the mean of the two replicates.

Subject	*Series* 1	2	3	4	5	*Mean*
A	25.8	24.0	28.9	34.0	25.6	27.7
B	23.0	19.2	24.7	21.4	28.8	23.4
M	25.0	26.1	23.0	25.9	23.1	24.6
S	22.6	25.8	22.4	26.4	21.5	23.7
Mean	24.1	23.8	24.8	26.9	24.8	

Table A8.—Warm-phase thumb skin temperature (°C). Each value is the mean of the two replicates.

Subject	*Series* 1	2	3	4	5	*Mean*
A	35.8	36.0	35.9	34.5	35.9	35.6
B	33.6	31.0	35.9	31.8	35.9	33.7
M	35.8	35.1	34.5	35.9	35.9	35.4
S	32.0	36.0	35.5	35.7	30.9	34.0
Mean	34.3	34.6	35.5	34.5	34.7	

Table A9.—Warm-phase body temperature and oxygen consumption. Summary of significance tests in analyses of variance.

	Source of variation *Series*	*Subjects*	*Interaction*
Rectal temperature	*	†	N.S.
Oxygen consumption	N.S.	†	*
Skin temperature			
Abdomen	N.S.	N.S.	N.S.
Thigh	*	†	N.S.
Toe	N.S.	N.S.	N.S.
Thumb	N.S.	N.S.	N.S.

† Significant at the 0.1% level.
* Significant at the 5% level.
N.S. Not significant.

Table A10.—Cold-phase body temperature and oxygen consumption. Mean values of the eight observations for each series.

	Series 1	2	3	4	5
Rectal temperature change† (°C)	−0.15	0.00	0.24	0.09	−0.37
Oxygen consumption* (ml/min)	482	441	467	440	454
Metabolic rate (kcal/m²/hr)	74.9	68.9	72.6	69.1	70.5
Skin temperature (°C)					
Abdomen—observed*	25.8	26.7	26.7	27.1	26.3
—adjusted	26.6	26.2	26.7	26.6	26.5
Thigh	25.4	26.3	25.9	26.4	26.0
Toe—observed	13.3	12.6	12.8	12.6	13.1
—adjusted	14.0	12.2	12.8	12.2	13.2
Thumb	14.0	13.9	13.5	13.4	14.6

† Differences between series means significant at 0.1% level.
* Differences between series means significant at 5% level. Significant differences for comparing means (5% level):
Rectal temperature: 0.24°C.
Oxygen consumption: 30 ml/min.
Metabolic rate: 4.8 kcal/m²/hr.
Means and significant differences for metabolic rate were obtained by conversion from the values for oxygen consumption. A separate analysis of variance for metabolic rate was not done.

Table A11.—Cold-phase rectal temperature change (°C). Each value is the mean of the two replicates.

Subject	Series 1	2	3	4	5	*Mean*
A	−0.25	−0.08	+0.16	+0.06	−0.28	−0.08
B	−0.24	+0.08	+0.38	+0.31	−0.44	+0.02
M	+0.49	+0.36	+0.54	+0.26	+0.16	+0.36
S	−0.58	−0.34	−0.10	−0.26	−0.91	−0.44
Mean	−0.15	0.00	+0.24	+0.09	−0.37	

Table A12.—Cold-phase oxygen consumption (ml/min). Each value is the mean of the two replicates.

Subject	Series 1	2	3	4	5	*Mean*
A	542	498	479	486	497	501
B	496	498	485	438	432	470
M	498	420	503	468	451	468
S	390	346	401	366	437	388
Mean	482	441	467	440	454	

Table A13.—Observed values of cold-phase abdomen skin temperature (°C). Each value is the mean of the two replicates.

Subject	1	2	*Series* 3	4	5	*Mean*
A	26.8	28.5	27.0	27.8	27.8	27.6
B	25.4	27.2	25.7	26.7	24.8	26.0
M	23.4	25.4	26.0	26.9	25.0	25.3
S	27.6	25.7	28.0	27.0	27.8	27.2
Mean	25.8	26.7	26.7	27.1	26.3	

Table A14.—Adjusted* values of cold-phase abdomen skin temperature (°C). Each value is the mean of the two replicates.

Subject	1	2	*Series* 3	4	5	*Mean*
A	27.7	28.0	27.0	27.2	27.8	27.5
B	26.3	26.7	25.6	26.4	24.9	26.0
M	24.1	25.0	26.3	26.2	25.0	25.3
S	28.3	25.2	27.9	26.7	28.2	27.3
Mean	26.6	26.2	26.7	26.6	26.5	

* Adjusted by means of the regression equation

$$Y_a = Y_o + 0.0560\ (x - 110.3),$$

where Y_a is the adjusted and Y_o the observed value for skin temperature of the abdomen (°C), and x the observed cold stress (kcal/m²/hr).

Table A15.—Cold-phase thigh skin temperature (°C). Each value is the mean of the two replicates.

Subject	1	2	*Series* 3	4	5	*Mean*
A	25.2	27.0	26.6	27.1	26.8	26.5
B	25.2	26.2	24.2	25.0	24.1	25.0
M	23.4	24.5	25.5	25.6	25.0	24.8
S	27.8	27.6	27.2	28.0	28.2	27.8
Mean	25.4	26.3	25.9	26.4	26.0	

Table A16.—Observed values of cold-phase toe skin temperature (°C). Each value is the mean of the two replicates.

	Series					
Subject	1	2	3	4	5	*Mean*
A	12.8	13.0	12.9	13.3	12.5	12.9
B	13.6	12.4	12.9	11.6	13.4	12.8
M	13.8	13.0	13.3	13.4	14.0	13.5
S	13.1	12.2	12.2	12.2	12.6	12.4
Mean	13.3	12.6	12.8	12.6	13.1	

Table A17.—Adjusted* values of cold-phase toe skin temperature (°C). Each value is the mean of the two replicates.

	Series					
Subject	1	2	3	4	5	*Mean*
A	13.6	12.6	12.9	12.8	12.5	12.9
B	14.5	11.9	12.8	11.3	13.5	12.8
M	14.4	12.6	13.6	12.8	14.0	13.5
S	13.8	11.7	12.1	11.9	13.0	12.5
Mean	14.0	12.2	12.8	12.2	13.2	

* Adjusted by means of the regression equation

$$Y_a = Y_o + 0.0516\ (x - 110.3),$$

where Y_a is the adjusted and Y_o the observed value for skin temperature of the toe (°C), and x the observed cold stress (kcal/m2/hr).

Table A18.—Cold-phase thumb skin temperature (°C). Each value is the mean of the two replicates.

	Series					
Subject	1	2	3	4	5	*Mean*
A	14.0	13.9	14.3	13.6	13.5	13.8
B	13.4	13.2	13.1	12.4	14.0	13.2
M	15.6	14.2	13.8	14.4	17.7	15.2
S	13.2	14.4	12.9	13.4	13.0	13.4
Mean	14.0	13.9	13.5	13.4	14.6	

Table A19.—Cold-phase body temperature and oxygen consumption. Summary of significance tests in analyses of variance and covariance.

	Source of variation		
	Series	*Subjects*	*Interaction*
Rectal temperature change	†	†	N.S.
Oxygen consumption	*	†	$.10 > P > .05$
Skin temperature			
Abdomen—observed	*	†	‡
—adjusted	N.S.	†	‡
Thigh	N.S.	†	N.S.
Toe—observed	N.S.	$.10 > P > .05$	N.S.
—adjusted	N.S.	$.10 > P > .05$	N.S.
Thumb	N.S.	†	$.10 > P > .05$

† Significant at the 0.1% level.
‡ Significant at the 1% level.
* Significant at the 5% level.
N.S. Not significant.

Table A20.—Cold-phase body temperature and oxygen consumption. Error regression coefficients from analyses of covariance.

Affected variate (*y*)	*Affecting variate* (*x*)	*Error regression coefficient* (*b*)	*Significance of* (*b*)
Rectal temperature change (°C)	Test cold stress (kcal/m²/hr)	0.0127	$.20 > P > .10$
Oxygen consumption (ml/min)	,,	0.153	$P > .20$
Skin temperature			
Abdomen	,,	−0.0560	$P < .05$
Thigh	,,	−0.00535	$P > .20$
Toe	,,	−0.0516	$.10 > P > .05$
Thumb	,,	−0.0142	$P > .20$
Rectal temperature (°C)	Relative humidity (%)	−0.00325	$P > .20$
,, ,, ,,	Mean radiant temperature (°C)	−0.0731	$P > .20$
,, ,, ,,	Body weight (kg)	0.0262	$P > .20$
,, ,, ,,	Surface area (m²)	2.21	$P > .20$
Cold-phase oxygen consumption (ml/min)	Warm-phase oxygen consumption (ml/min)	0.663	$P = .20$

Table A21.—Ranked physical characteristics and physiological responses of subjects. The highest value is indicated by (1) and the lowest by (4) in each case.

Variable	*Subjects* M	B	A	S
Body weight (1959 average)	1	2	3	4
Surface area (1959 average)	1	2	3	4
Skinfold thickness (Dec. 1960)	2	1	3	4
Warm phase				
Rectal temperature	1	4	3	2
Oxygen consumption	1	3	2	4
Abdomen skin temperature	2	3	4	1
Thigh skin temperature	2	4	3	1
Toe skin temperature	2	4	1	3
Thumb skin temperature	2	4	1	3
Cold phase				
Rectal temperature change	1	2	3	4
Oxygen consumption	3	2	1	4
Abdomen skin temperature*	4	3	1	2
Thigh skin temperature	4	3	2	1
Toe skin temperature*	1	3	2	4
Thumb skin temperature	1	4	2	3

* Both observed and adjusted values.

Table A22.—Notes on the shivering of Subject M in Series 3 (second exposure).

Time (min)	*Shivering activity*
1	Piloerection occurred as soon as blankets were removed.
3	No sign of shivering.
5-10	Intermittent flickers in abdominal and lower intercostal muscles.
13	Abdominal flickers becoming stronger and steadier; an occasional tonic contraction of upper abdominal muscles occurs, causing indrawing of the lower ribs.
15	Pectoralis major now shows intermittent flickers. No activity in limbs.
21	Pectoralis major flickers stronger and more frequent. Otherwise no change.
22	Pectoralis major contractions now shaking arms and chest. No activity in lower limbs.
28	Slow increase in severity of all shivering. Still no activity in thighs.
42	Thigh adductors and sartorius now intermittently flickering with occasional tonic spasms. Duration of trunk shivers now 30-60 seconds, separated by 20-second periods of fine flickering. Intermittent shaking tremors.
52	Violent shaking tremors lasting 5-10 seconds.
58	Violent shaking tremors lasting 20 seconds and occurring more frequently — every 30-60 seconds. Quadriceps femoris on both sides now show occasional tonic contractions. An occasional unilateral abdominal tonic contraction swings the hips sharply.
73	A change in pattern. Now brisk shudders, lasting 2-4 seconds, occur every 15-20 seconds; between shudders there is almost complete relaxation, with only a faint flicker here and there.
92	Little change during the past 20 minutes in the type, intensity or frequency of shivering.

Table A23.—Notes on the shivering of Subject S in Series 2 (second exposure). Oxygen consumption and body temperature for this exposure are shown in Fig. 27.

Time (min)	*Shivering activity*
15	No sign of shivering or any other muscle activity since commencement of cold exposure.
20	No muscle action.
25	No muscle action.
28	No muscle action. Not even piloerection.
31	Very faint contractions in epigastrium during expiration. They are clonic contractions, not fibrillation.
34	Epigastric contractions a little stronger and more regular.
39	Epigastric movement more coarse. Left pectoralis major flickered for one second.
43	Right sartorius, and adductor group of left thigh, fibrillating rapidly with moderate amplitude. Piloerection on right thigh postero-medially; none visible on trunk or on anterior surfaces of limbs.
46	Left sartorius now fibrillating, as coarsely as the right one.
57	Fibrillation generalised over abdomen, pectoralis major, and thighs. Intercostal muscles show expiratory flickers.
67	Fibrillation generalised, continuous, and coarse. Intermittent generalised shudders.
85	Moderate shivering, generalised but now steady.
95	No change.

(Note on sensation. Until 50 minutes the subject felt merely comfortably cool, but thereafter he felt progressively colder.)

Table A24.—Mean heart rate (beats/min) during warm phase. Each value is the average of the two replicates.

Subject	*Series* 3	4	5	*Mean*
A	64.9	66.0	68.5	66.5
B	72.6	66.7	68.1	69.1
M	50.0	59.9	61.4	57.1
S	59.0	57.6	58.6	58.4
Mean	61.6	62.6	64.2	62.8

Table A25.—Mean heart rate (beats/min) during cold phase. Each value is the average of the two replicates.

Subject	*Series* 3	4	5	*Mean*
A	77.0	75.5	74.2	75.6
B	76.4	75.8	74.1	75.4
M	55.3	53.9	56.6	55.2
S	58.4	54.5	62.1	58.3
Mean	66.8	64.9	66.7	66.2

Table A26.—Change (cold phase minus warm phase) in mean heart rate (beats/min). Each value is the average of the two replicates.

Subject	Series 3	Series 4	Series 5	Mean
A	12.1	9.5	5.7	9.1
B	3.8	9.1	6.0	6.3
M	5.3	—6.0	—4.8	—1.9
S	—0.6	—3.1	3.5	—0.1
Mean	5.2	2.3	2.5	3.4

Table A27.—Rewarming-phase rectal temperature change (°C) from warm-phase values. Each value is the mean of the two replicates. The figures in brackets indicate the time (min) since the end of the cold exposure.

Subject	Series 1	Series 2	Series 3	Series 4	Series 5	Mean
A	—0.33(44)	0 (68)	—0.06(49)	+0.10(58)	—0.22(56)	—0.10(55)
B	—0.48(17)	—0.48(48)	+0.16(60)	—0.52(62)	—1.11(58)	—0.49(49)
M	—0.08(56)	0 (61)	+0.11(60)	0 (53)	—0.40(44)	—0.07(55)
S	—0.98(38)	—0.29(63)	—0.21(58)	—0.67(55)	—0.70(65)	—0.59(56)
Mean	—0.47(39)	—0.19(60)	0 (56)	—0.27(57)	—0.61(56)	

Table A28.—Rewarming-phase abdomen skin temperature (°C). Each value is the mean of the two replicates.

Subject	Series 1	Series 2	Series 3	Series 4	Series 5	Mean†
A	31.4	34.6	30.7	33.3	31.6	32.6
B	*	32.0	31.4	32.0	31.3	31.7
M	30.2	30.4	30.6	30.6	29.0	30.1
S	*	32.0	33.4	33.4	33.4	33.1
Mean	*	32.2	31.5	32.3	31.3	

* Not observed.

† Series 1 excluded.

Table A29.—Rewarming-phase thigh skin temperature (°C). Each value is the mean of the two replicates.

Subject	*Series* 1	2	3	4	5	*Mean*†
A	31.0	29.9	29.6	29.9	29.9	29.8
B	*	28.3	28.2	26.6	29.6	28.2
M	28.0	28.6	28.6	28.0	29.8	28.7
S	*	31.8	31.4	30.1	29.4	30.7
Mean	*	29.6	29.4	28.6	29.7	

* Not observed.

† Series 1 excluded.

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