

Ergonomic aspects of cold stress and cold adaptation

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BUDD GM. Ergonomic aspects of cold stress and cold adaptation. *Scand J Work Environ Health* 1989;15(suppl 1):15–26. In contrast to the simplified, unvarying, and rigidly controlled conditions that characterize laboratory studies of human responses to cold, normal work in cold regions is characterized by a complex and unstable thermal environment, intermittent cold exposure and exercise, and the freedom to adjust clothing and activity for comfort. These “ergonomic” aspects profoundly modify the impact of a cold environment on people’s health, comfort, and performance. A review of recent field studies in the Antarctic shows that the supposed “tropical microclimate” of clothed people in the cold is an oversimplification. People tend to be alternately chilled and overheated, and the accompanying exercise of the vascular responses provides a potential stimulus for vasomotor adaptation. Significant and substantial changes in men’s responses to standardized whole-body cold exposures, observed on eight Antarctic expeditions, show that general acclimatization to cold develops as an increase in tissue insulation, which is mediated by an enhanced vascular response to cold.

Key terms: Antarctica, body composition, cold acclimatization, cold-weather clothing, microclimate, physical training, polar travel, responses to cold, thermal comfort, thermal stress.

Unsolved problems of clothing and adaptation continue to reduce the safety and efficiency of people living and working in cold regions. Equipped as they are with whole-body evaporative cooling but no body fur, humans have powerful physiological defenses against heat but very limited defenses against cold. In the cold they must therefore rely heavily upon clothing and shelter, reinforcing (and largely replacing) the continuously varying fine control of physiological temperature regulation with the intermittently adjusted coarse control of behavioral temperature regulation.

Many investigations of human responses to cold have been laboratory studies, usually of only a few hours’ duration, in which the subjects’ environment and behavior, in particular their activity and clothing, were rigidly controlled and usually kept constant. Considerable extrapolation is required to apply the results to normal work in cold regions, in which the thermal environment is complex and unstable, exercise and cold exposure are intermittent, and people are free to adjust their clothing and activity for comfort. Yet it is these “ergonomic” aspects that determine the impact of a cold environment on a worker’s health, comfort, and performance. The examples given in the following discussion have been drawn from field research in the Antarctic, but the conclusions are relevant to most cold environments, and in some respects to hot environments as well (1). After a brief survey of the theoretical background and of laboratory investigations, evidence is reviewed concerning three fundamental questions, namely, (i) how cold are people in the Antarctic,

(ii) is there an effective stimulus to acclimatization, and (iii) does cold acclimatization in fact occur?

Stress, strain and adaptation

Figure 1A shows the theoretical basis of the aforementioned questions in terms of the customary engineering model of stress and strain. In laboratory experiments all elements of stress and strain can be precisely measured, and thus the dose-response relationship between them can be established. If adaptation develops, it is apparent as a change in this relationship so that the same stress evokes a different degree of strain, eg, the increased sweat rate and lower heart rate that accompany acclimatization to heat.

Unfortunately, the real world is more complicated (figure 1B). A person’s behavior, which itself may change through behavioral adaptation (figure 1C), profoundly modifies the stress experienced so that the effective stress may be very different from the potential stress, however precisely measured that potential stress may have been. And the strain produced by the resulting effective stress is itself greatly modified not only by physiological adaptation but by a host of other biomedical factors, the combined effect of which is to produce large differences between individuals.

Behavioral and biomedical modifiers thus introduce a large measure of uncertainty into attempts to predict strain from environmental measurements, and so reduce the reliability of any standards that may be set. Much of the subject matter of environmental ergonomics concerns attempts to cope with this uncertainty. In the present context of acclimatization to cold, the simple model of figure 1A is the basis of the laboratory tests used to seek evidence of adaptation, whereas the complex model of figure 1B must be the basis for our

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experimental design and for the interpretation of any observed changes. Historically, the two main uncertainties in field studies of cold acclimatization have been (i) has the attenuation of the environmental cold stress by clothing and shelter effectively eliminated the stimulus to acclimatization, and (ii) are observed changes in the subject's responses due to acclimatization or to concomitant changes in other biomedical factors such as fatness or fitness?

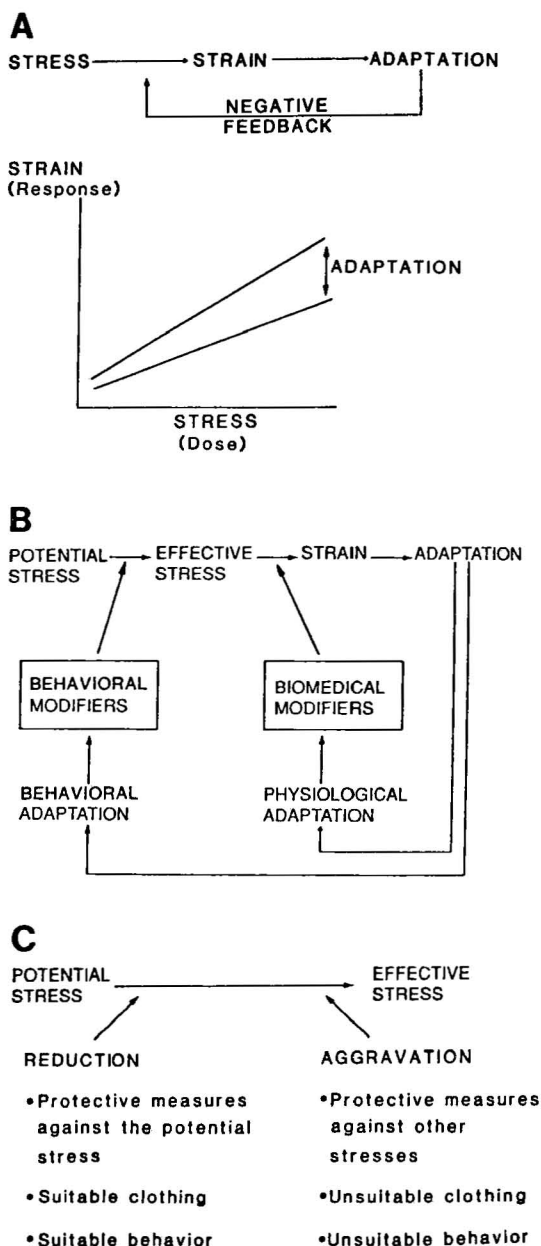


Figure 1. Stress, strain, and adaptation: the basic idea (A), possible complications (B), and the behavioral modifiers (C).

Cold stress in the laboratory

Controlled exposures in climatic chambers or cold rooms have been used in many attempts to induce general acclimatization, and they provide one of the most informative means of detecting it.

Attempts to induce general acclimatization

As a means of trying to induce acclimatization (or acclimation, as laboratory adaptations are sometimes called), cold room exposures have the advantages that (i) since the subjects are deprived of their customary behavioral means of reducing their cold exposure, it can be ensured that they are cold, and (ii) the exact dose (degree and duration) of cold to which they are subjected can be measured, in contrast to the uncertainties of trying to estimate how much cold stress, if any, is sustained under natural conditions. The main disadvantages of cold room acclimation are that (i) the experimenter is obliged to make more or less arbitrary decisions about the nature, severity, duration, and frequency of the exposures, in the absence of any information on the kind of exposure likely to be the most effective, and (ii) even if some kind of adaptation does develop, it may not be the same as that which develops under natural conditions, as is the case with artificially and naturally acclimatized rats (2).

Detection of general acclimatization

The most direct way to seek evidence of acquired general acclimatization is to expose subjects to rigorously controlled and standardized cold stress from time to time and see whether their responses change.

During cold exposure tests heat loss usually exceeds heat production and thus leads to a heat debt so that:

$$\text{Heat loss} = \text{heat production} + \text{heat debt.}$$

Heat production throughout the exposure is readily measured by standard techniques, and heat debt can be calculated with greater or lesser degrees of precision from measurements of rectal and skin temperature. Heat loss from the whole body can be measured directly only with a calorimeter, but a reasonable approximation can be calculated as the sum of heat production and heat debt. If heat loss were to be reduced as a result of an increase in tissue insulation, the benefit might be apparent as either reduced heat production with an unchanged heat debt, unchanged heat production with a reduced heat debt, or a reduction in both heat production and heat debt.

Increased tissue insulation can be brought about in two ways — by an increased thickness of subcutaneous fat or by changes in peripheral circulation that enhance heat conservation. Subcutaneous fat can be measured as skinfold thickness, but how is one to measure changes in the peripheral circulation? Measurements of skin temperature can sometimes be a guide, but their usefulness is limited by the great spatial and temporal

variability of skin temperature (3). Consequently, many authors, whose work has been reviewed elsewhere (4, 5), have found themselves confronted with an “unbalanced heat equation” when they sought to interpret their findings in terms of skin temperature.

There is available, however, a simple and informative index of the changes in peripheral circulation, ie, the paradoxical fluctuation in core temperature that occurs in response to body cooling or warming. The intensity of the vasomotor responses is reflected in the steepness and extent of both the rise in core temperature as vasoconstriction develops during cooling (6) and the subsequent fall in core temperature as vasoconstriction relaxes during rewarming (7). Core temperature has also been observed to rise and fall, sometimes accompanied by contrary changes in skin temperature, in response to spontaneous cyclic fluctuations in vasomotor tone (3, 4, 8, 9). These paradoxical fluctuations in core temperature have been variously attributed to a reduced return of cooled venous blood (10, 11), a temporary imbalance between heat production and heat dissipation, heat exchange between adjacent arteries and veins (12), and a compensatory vasodilatation in the splanchnic blood vessels (13–15). Whichever explanation is correct, the practical application is that such paradoxical fluctuation in core temperature can provide a useful index of the onset, the nature (vasoconstriction or vasodilatation), and the intensity of peripheral vascular responses.

How cold are people in the Antarctic?

Just how cold are people in the Antarctic? One view is that the effective cold stress is negligible because of clothing and shelter. Amundsen (16) believed that the cold was not a problem if one had “good and serviceable” fur clothing; Stefansson (17) remarked that the air in contact with a well-dressed Eskimo’s skin was always at the temperature of “a tropical summer”; measurements on fur-clad Lapps (18) and Eskimos (19) have shown that their skin temperatures remain high during outdoor work and rest at subzero temperatures; and it was concluded (18) that clothed humans in the cold enjoy an “almost tropical” microclimate.

This view would perhaps have received little support from three members of Scott’s 1911 expedition. They made a five-week midwinter sledge journey (without fur clothing) in temperatures as low as -60°C . Writing of the convulsive shivering that he, Wilson, and Bowers endured each night in their iced-up sleeping bags, Cherry-Garrard (20) wrote: “They talk of chattering teeth: but when your body chatters you may call yourself cold [p 241].” Yet he also wrote “On the most bitter days . . . it seemed that we must be sweating [p 237],” and he noted that the sweat promptly turned to ice in their clothing.

An examination of the avenues of heat exchange confronting a clothed person in the Antarctic (table

Table 1. Heat exchange of clothed humans in polar climates.^a (Calculations based on data from reference 21)

	Watts
Heat gain	
Metabolism	70—1400
Sunlight	0—750
Total	70—2150
Heat loss	
Convection	300—3500
Radiation to sky and terrain	400—1000
Total	700—4500

^a Range of variation in air temperatures of no lower than -30°C .

1), even in temperatures no lower than -30°C , reveals that the person has to strike a balance between the heat gained from metabolism and sunlight and the heat lost to the cold wind, sky, and terrain. All these factors vary widely and independently so that the resultant heat gains and losses can range over several kilowatts. Physiological temperature regulation alone cannot cope with such massive heat exchanges, and it is thus reinforced (and to a large extent replaced) by behavioral regulation — which consists of the selection and timely adjustment of clothing, supplemented by a retreat to shelter when conditions become intolerable.

The trouble with behavioral regulation is that clothing adjustments, which are frequently needed because of changes in activity and weather, must compete with the other tasks that claim one’s time and attention (1, 22) — and when such adjustments are delayed or inadequate, one becomes uncomfortably cool or warm.

Field studies have therefore been undertaken, over a period of 30 years (from 1957 through 1986), to determine how often Antarctic expeditioners experience thermal discomfort or thermal stress and whether such thermal imbalance might provide an effective stimulus to acclimatization. Thermal discomfort (23) and associated physiological responses were recorded, together with observations of clothing, activity, and weather, when men were working indoors and outdoors at stations in the Antarctic and the sub-Antarctic, traveling by dog sledge and by snowmobile on the sea ice and the Antarctic Plateau, and backpacking in the wet and cold Antarctic climate of Heard Island.

Frequency of thermal discomfort

Figure 2 summarizes the available evidence on the frequency of thermal discomfort in the Antarctic. Indoors, whether in heated buildings or in tents, the men were rarely too cool, although sometimes they were too warm. Outdoors, by contrast, they were uncomfortable during as many as 55 % of the observations. Discomfort was the most frequent in the strenuous outdoor activities of dog sledging and backpacking.

Discomfort outdoors at the stations was due equally to heat and cold. Only during backpacking in the

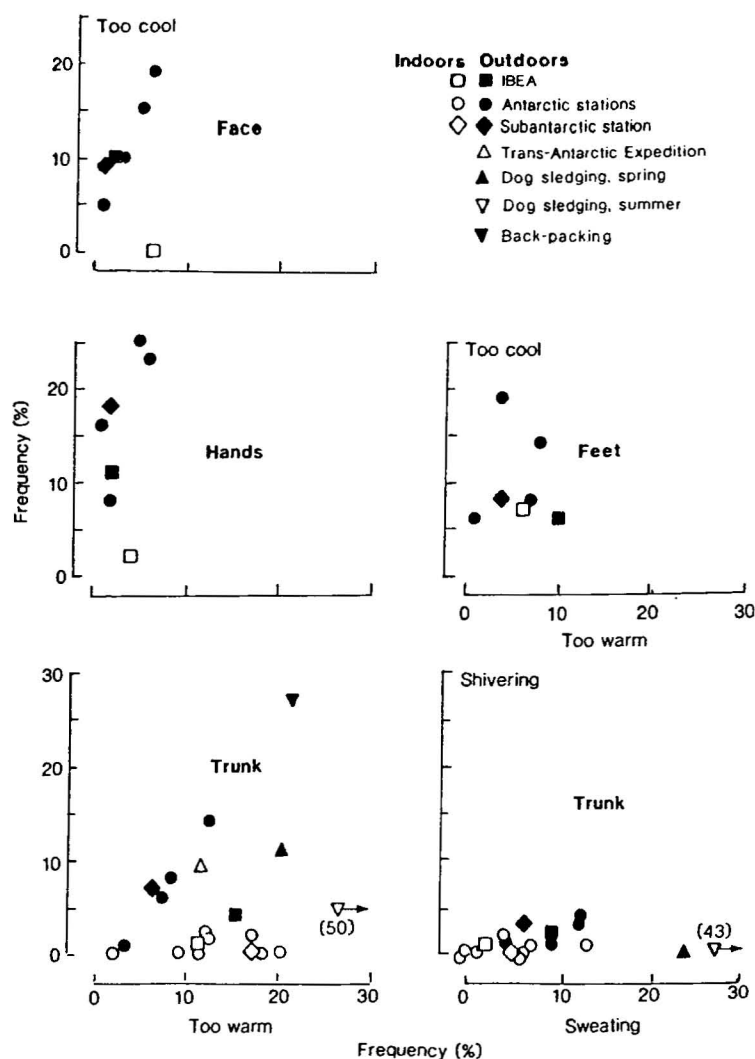


Figure 2. Thermal discomfort indoors and outdoors. Each point is the average of all the observations made on one expedition or journey. The data are from references 22, 24–29. [IBEA = a snowmobile trip during the International Biomedical Expedition to the Antarctic (28)] [Reproduced, with permission, from reference 28]

wet, cold climate of Heard Island, where it is difficult to keep clothing dry, were the men too cool (27 %) more often than they were too warm (21 %). Conversely, during travel by dog sledge and snowmobile the men were too warm more often than they were too cool, especially in summer when solar radiation is intense. Indeed, during summer journeys by dog sledge, the men were too warm in 50 % of the observations, were sweating in 43 %, and experienced deep body temperatures as high as 38.7°C; as a consequence they developed, in the subzero cold of the Antarctic, acclimatization to heat (29).

The degree of discomfort, and of sweating, numbness, and pain, was predominantly mild — as would be expected, since moderate or severe discomfort usually provokes an effective behavioral response to correct it. However, during work which required a wide range of activity with no opportunity to adjust clothing (such as taking snow samples for trace-element analysis in a glaciology pit), discomfort was two to three times more frequent and was also more severe.

The men differed widely in the kind and degree of discomfort they reported, partly as a result of differences in their habitual activity and clothing and partly because of their individual preference for being too warm rather than too cool, or vice versa.

Effects of thermal environment

The microclimate of clothed men in the Antarctic (25, 30, 31) has shown a different pattern from that observed for Lapps and Eskimos (19). Skin temperature and subclothing temperature were at normal indoor levels (33–35°C) when men were in buildings or tents but fell by 6°C or more when they went outdoors, in spite of the outdoor clothing worn. The fall in skin temperature was greater in cold or overcast weather (figure 3), despite the additional clothing worn under such conditions.

Men traveling by dog sledge were uncomfortable more often in the colder weather (figure 3), because of a greater frequency of discomfort from cold with

little reduction in the frequency of discomfort from heat and sweating (25). Increasing discomfort in the colder weather was also experienced at the Antarctic stations, especially for the face and the extremities (27). In the coldest weather the men's faces, hands, and feet were uncomfortably cool in 36, 33, and 25 % of the observations, respectively, that were made at the stations, and in 33, 19, and 12 %, respectively, of those made during a snowmobile trip (28). However, on the snowmobile trip colder weather did not cause more frequent coldness of the trunk, because of the greater use of down-filled clothing which gave the total clothing ensemble an insulation of 3 clo units (32).

Effects of activity

Outdoor work in the Antarctic is strenuous, and heat production is often of the order of 500 W (33, 34). Men traveling by dog sledge or snowmobile (25, 28) felt warmer and sweated more often when they worked harder (figure 4). During the most strenuous work they reported sweating in 33 % of the observations when dog sledging and in 58 % when traveling by snowmobile. Besides sweating more often, they also sweated more profusely. Clothing records during the snowmobile trip (28) showed that the overheating during exercise was due to the men's failure to reduce their clothing enough to compensate for the extra heat production, so that heat storage and sweating were inevitable. The feet shared in the discomfort, being uncomfortably warm in 39 % of the observations made during heavy work.

Sweat loss and the water exchanges of clothing

During a 10-week snowmobile trip on the Antarctic Plateau, in air temperatures ranging from +2 to -29°C, sweat loss (including insensible perspiration) during a 9.7 h workday ranged from 176 to 995 g (35) and varied with air temperature. The water exchange of the clothing ranged from a gain of 820 g to a loss of 430 g. The water uptake of the clothing was proportional to the sweat rate, but the progressive wetting of clothing observed in laboratory studies (36) did not occur, apparently because of periodic exposure to conditions favorable to drying in sunny weather and in warmed environments indoors.

Current problems with polar clothing

The preceding summary of findings reflects the long-standing and still unsolved problems of cold-weather clothing, as discussed elsewhere (1). Clothing that provides even 3 clo units of insulation tends to be excessively heavy, bulky, and stiff; and because its insulation cannot be reduced conveniently enough, the enhanced protection from cold is gained at the cost of more frequent overheating and sweating during exercise. The frequencies of a cold face and hands reflect the difficulties of designing a face mask that can cope with icing from frozen breath, and of reconciling the

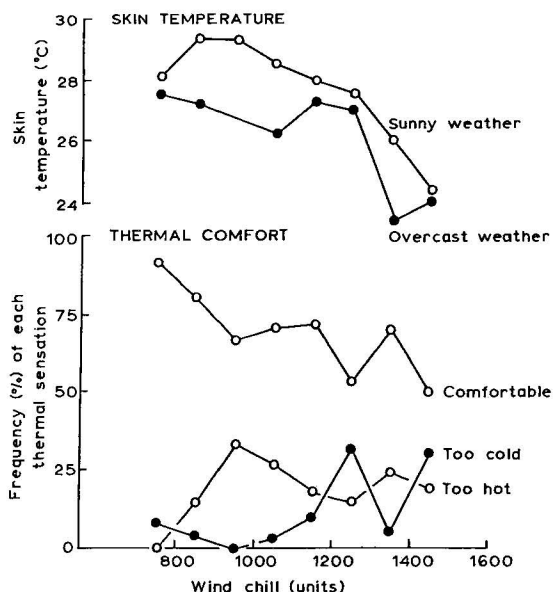


Figure 3. Effects of thermal environment on men traveling by dog sledge in spring — skin temperature of the medial thigh, and the distribution of thermal discomfort, in each class interval of wind chill. [Reproduced, with permission, from reference 26]

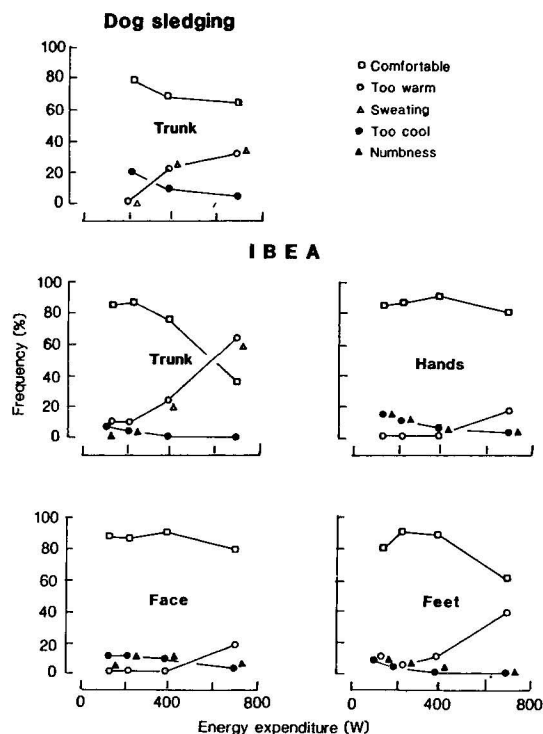


Figure 4. Effects of activity on men traveling by dogsledge and by snowmobile in similar thermal environments — the distribution of thermal discomfort outdoors at each grade of work. The distribution of cold-induced pain, omitted for clarity, was similar to that for numbness. The data for dog sledging are from reference 25. [Reproduced, with permission, from reference 28]

conflicting requirements of the hands for protection and manipulative performance (37, 38). The equal frequencies of uncomfortably warm and cold feet reflect (like those of the trunk) the lack of opportunity to vary the insulation of footwear to match variations in environment and activity (39), with the result that sweating wets the insulation and increases the risk of cold injury.

Is there an effective stimulus to acclimatization?

The aforementioned findings show that present-day Antarctic clothing greatly reduces cold stress but does not eliminate it. The notion that a permanent "tropical microclimate" is maintained beneath the clothing thus appears to be an oversimplification. People tend to be alternately chilled and overheated, and the accompanying exercise of the vasomotor responses would seem to be a remarkably appropriate stimulus for the enhanced vascular response to cold which has been found to develop, as described in the following discussion. Likewise, the frequent occurrence of cold-induced numbness and pain appears to provide an appropriate stimulus for the local acclimatization which has been reported for the face (22, 40) and hands (30, 41, 42). The infrequency of shivering is consistent with the finding that acclimatization in the Antarctic does not increase the metabolic response to cold (22, 26). Conversely, the elevated core temperatures and heavy sweating reported during summer sledging were appropriate stimuli for the observed acclimatization to heat (29). There is evidence that cold exposure has an antagonistic effect on heat tolerance (43), but measurements of tolerance to both heat and cold throughout an Antarctic winter have yet to be undertaken.

Does cold acclimatization in fact occur?

Evidence of acclimatization to cold has been sought on many polar expeditions over the past 40 years. Comprehensive reviews of biomedical research on such expeditions have been published by Edholm & Lewis (44), Edholm & Gunderson (45), and Gunderson (46), and research on thermal stress and acclimatization has also been reviewed earlier (4, 22, 26). The present account is therefore restricted to a summary of the main findings concerning general acclimatization.

Whole-body cold exposures in controlled and standardized environments have been used to test for the development of acclimatization during (i) a year or more on the Antarctic continent, on seven expeditions, (ii) a summer expedition in the severe wet and cold Antarctic climate of Heard Island, and (iii) an attempt to induce preacclimatization to cold, by means of cold baths, before an expedition's departure from Australia.

Wintering parties in Antarctica

Little America 1957. Eight men were exposed nude to an ambient temperature of 17°C for 2 h in autumn, winter, and spring (47). In winter and spring the metabolic response to cold was significantly less than it had been in the autumn, yet the heat debt was no greater, a finding implying that heat loss had been reduced by an increase in tissue insulation. The changes in heat production were poorly correlated with changes in fatness, and it seems likely that the increased tissue insulation was mainly due to an enhanced vasomotor response to cold.

Mawson 1959. Four men were tested twice in each of five series over a period of 17 months (4, 48). In each test they were exposed nude to an ambient temperature of 10°C for 95 min. Series 1 and series 5 were done in Australia, immediately before and after the expedition, and series 2, 3, and 4 were done at Mawson in the Antarctic autumn, spring, and summer. Figure 5 shows that in series 1 the vasoconstrictor response to cold, as reflected in the paradoxical rise in rectal temperature, was slow in onset and small in degree. At Mawson (series 2–4) it was prompt, strong, and well-sustained; and in series 5, back in Australia once more, there was an early but weak vasoconstrictor response which maintained the rectal temperature at its initial level for only 35 min, after which time the rectal temperature fell steeply to lower levels than in series 1.

The changes between series in the final value of the rectal temperature were statistically highly significant ($P < 0.001$), and they reflect a substantial improvement in the subjects' ability to defend core temperature during cold stress. In all four subjects, after 95 min of exposure the rectal temperature in series 3 was steady near or above the preexposure level, whereas in series 5, after the acclimatization had decayed, the rectal temperature was as much as 1°C lower and was falling steeply. Measurements made after an hour's rewarming showed that the changes in rectal temperature between series reflected real changes in heat debt and were not simply the result of a changed distribution of body heat as suggested by Carlson et al (49).

The changes in rectal temperature could not be explained by associated changes in fatness or physical fitness, and they were not due to some endogenous seasonal rhythm or to changes in day length, as are seasonal changes in the heat tolerance of cattle (50). However, they showed a clear relation to air temperature and were highest in the coldest weather. It was therefore concluded that the observed changes reflected the development and subsequent decay of general acclimatization to cold.

As regards the mechanism of acclimatization, it was clearly not mediated by an increased metabolic response to cold (figure 6) — in contrast to that of small animals, which develop an increased capacity to pro-

duce heat (nonshivering thermogenesis) from brown fat (51, 52). The average heat production was significantly less ($P < 0.05$) in series 2, 4, and 5 than it had been in series 1, but the changes between series were different for each subject and were unrelated ($P > 0.20$) to the subjects' changes in rectal temperature.

The improved ability to maintain rectal temperature without an accompanying increase in heat production implied an increase in tissue insulation. This increased insulation, as noted in the preceding discussion, was not due to increased fatness. Nor could it have been due to the reduced muscle perfusion or reduced air movement over the skin that might accompany a reduction in shivering, because changes in shivering and metabolism were unrelated to changes in rectal temperature. Indeed, in three subjects, heat production in series 3, when rectal temperature was at its highest, was the same as it had been in series 1. It was therefore concluded that the increased tissue insulation was in fact due to the enhanced vasoconstrictor response to cold that is apparent in the changes in rectal temperature.

The mechanism of acclimatization is well illustrated by one subject's response in series 2 (figure 7), in which there was a prompt rise in rectal temperature, a very

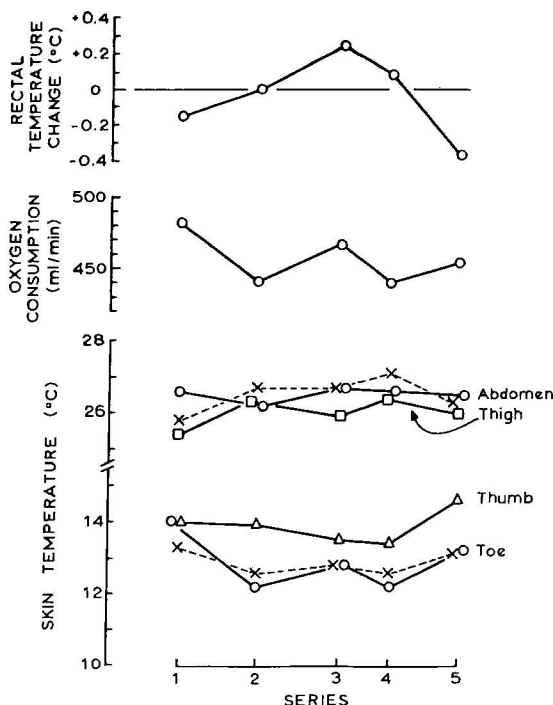


Figure 6. Responses of body temperature and oxygen consumption to cold — mean values of the eight exposures made in each of the five series of nude exposure experiments of the Mawson 1959 expedition. The distance between the series is proportional to time. The observed skin temperatures of the abdomen and the toe are shown by broken lines, and the values adjusted by analysis of covariance (on minor variations in the cold stress test) by solid lines. [Reproduced, with permission, from reference 4]

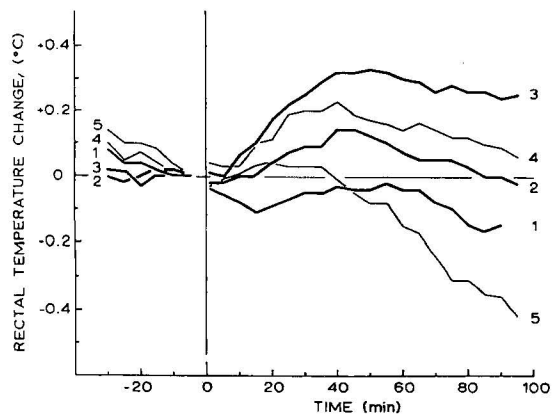


Figure 5. Rectal temperature change — mean values of the eight exposures made in each of the five series (shown by their respective numbers) of nude exposure experiments of the Mawson 1959 expedition. Zero time indicates commencement of the test cold exposure. [Reproduced, with permission, from reference 4]

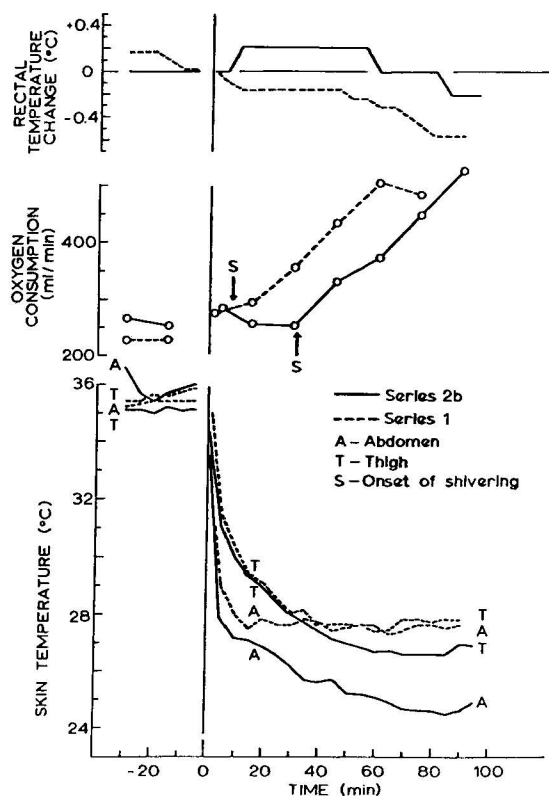


Figure 7. Body temperature, oxygen consumption, and onset of shivering of one subject in the second exposure of series 2 of the nude exposure experiments of the Mawson 1959 expedition, in comparison with his mean values in series 1. (Zero time = commencement of cold exposure) [Reproduced, with permission, from reference 4]

late metabolic response, and the lower skin temperatures that enhanced vasoconstriction would seem to imply [although, for reasons discussed elsewhere (5), consistent changes in skin temperature are infrequently observed]. Acclimatization thus appears to change the balance between the metabolic and vasoconstrictor responses to cold, in a manner reminiscent of an earlier comment, in another context, by Cannon & Keatinge (9). Referring to the fact that immersed fat men did not achieve their maximum tissue insulation until the water temperature was much lower than that required to elicit an increased metabolic rate, these authors commented that "their increase in metabolic rate was therefore unnecessary, in that they could have achieved thermal balance by vasoconstriction alone at these temperatures [p 338]." The results of this study suggest that the acclimatized person improves his thermal balance in just this way.

Mawson 1964. Five years later the Mawson investigation was repeated at the same station, in the same way, by a different observer using different subjects (5). Four men were tested twice in each of two series, one (series 1) immediately before leaving Australia and a second (series 2) at Mawson in late winter, 24 weeks after arriving in Antarctica. The results (figure 8) were identical to those of the 1959 study, rectal temperature at Mawson showing an earlier, higher, and better sustained rise than in Australia. The change was significant, and it could not be attributed to changes in fitness or fatness. Heat production could not be reliably

measured in series 2, but the onset, pattern, and intensity of shivering were the same in both series.

In keeping with the stronger vasoconstriction in series 2, the relaxation of vasoconstriction in the first 15 min of rewarming caused more than twice as great an "after-drop" in rectal temperature in series 2 as it had in series 1. Collins et al (7) have also observed that subjects with stronger vasoconstriction during cooling experience a greater after-drop on rewarming.

Series 2 was also characterized by large spontaneous fluctuations in rectal temperature (figure 9), as much as 0.5°C in 10 min, which occurred at much the same times as smaller fluctuations or pauses in cooling had occurred in series 1. The fluctuations in series 2 were attributed to an exaggeration, caused by the enhanced sensitivity and intensity of vasomotor responses in the acclimatized subject, of a normal cyclic variation in the vasomotor response to cold.

Halley Bay 1968. In the winter of 1968 Dr Denis Wilkins, at the British station at Halley Bay, investigated men's responses to a deliberate increase in daily cold stress (53). An "acclimatization group" of four men sat for 2 h/d, lightly clothed, in a cold room at -20°C for 14 successive days and were accompanied 1 d/week by a control group of three identically clothed men. Core temperatures throughout the exposures, and for 45 min of subsequent rewarming in a room at +16°C, were continuously measured by telemetry with temperature-sensitive "radio pills." Figure 10 shows that on the first day of exposure the acclimatization and

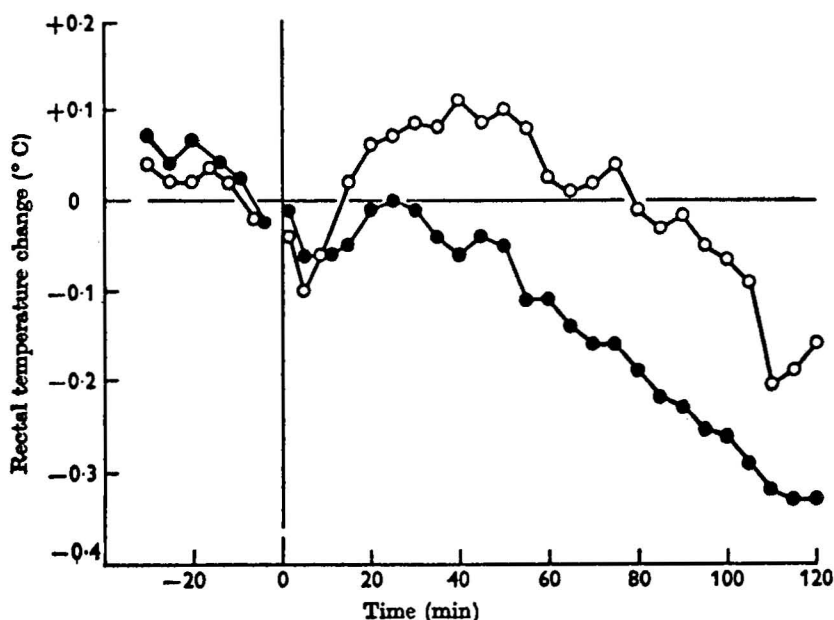


Figure 8. Rectal temperature change in Melbourne (filled circles) and Mawson (unfilled circles) — mean values of the eight exposures made in each series of the nude exposure experiments of the Mawson 1964 expedition. (Zero time = commencement of cold exposure) [Reproduced, with permission, from reference 5]

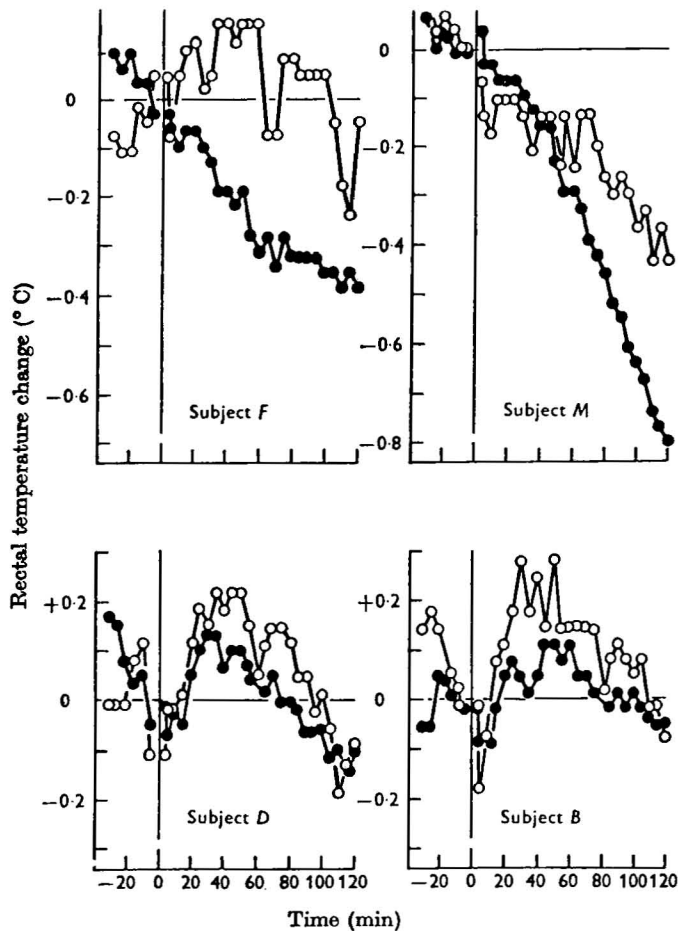


Figure 9. Rectal temperature change in Melbourne (filled circles) and Mawson (unfilled circles) — individual values (mean of two replicates) in each series of the nude exposure experiments of the Mawson 1964 expedition. (Zero time = commencement of cold exposure) [Reproduced, with permission, from reference 5]

control groups responded in an identical fashion. A small and transient immediate rise in core temperature, presumably indicative of natural acclimatization, was followed by a continuing fall to a final temperature 0.7°C below the preexposure values. Over the next 14 d the control group's responses remained unchanged, whereas the acclimatization group progressively developed higher and more sustained increases in core temperature, to the extent that on day 14 the core temperature after 2 h was less than 0.2°C below the preexposure values — an improvement of more than 0.5°C , which was statistically highly significant. The acclimatization group also showed, as had acclimatized subjects at Mawson (5), an exaggeration of their spontaneous fluctuations in core temperature and a greater after-drop in core temperature as the intensified vasoconstriction relaxed during the rewarming. The results thus confirmed those of the two previous studies at Mawson, and extended them by showing that in naturally acclimatized subjects additional habitual cold stress appears to provoke the accelerated development of a greater degree of acclimatization — in marked contrast to the generally negative results of at-

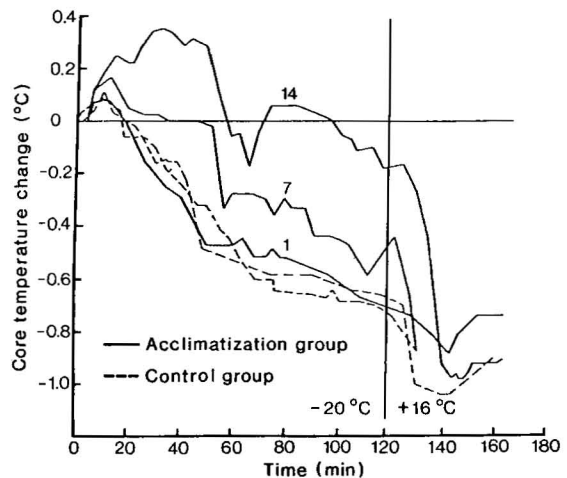


Figure 10. Core temperature change during clothed cold exposures and subsequent rewarming at Halley Bay in 1968 — mean values on the first, seventh, and fourteenth day (shown by their respective numbers) of artificial acclimatization. (Zero time = commencement of cold exposure) [Reproduced, with permission, from reference 53]

tempts to induce acclimatization by repeated or continuous exposures in cold rooms in temperate climates.

Other investigations. Bodey (54) reported that 12 men wintering at the Australian station Casey, when periodically tested for 2 h at an ambient temperature of 10°C, improved their ability to maintain rectal temperature. At the South African station SANAE in 1961, Wyndham and his colleagues (55) measured six men's responses during 90-min exposures to ambient temperatures of 5, 10, 15, and 27°C and found that the metabolic response to the lower air temperatures was less than it had been in comparable groups in South Africa. The authors concluded that tissue insulation had increased in Antarctica, and they attributed it to weight gain. The results of a subsequent investigation at SANAE in 1967 (56) were thought to support this view, and, in addition, to suggest that vasoconstrictor tone had increased.

Influence of changes in fitness and fatness

Two important confounding variables in field studies are the increased fitness and reduced fatness that often result from the physical exertion of life in snow country (25, 57–60) and can change responses to cold in a way that might be misinterpreted as evidence of acclimatization. Thus Adams & Heberling (61) and Heberling & Adams (62) reported that physical training alone could produce the changed responses to cold — increased skin temperature and heat production, and unchanged or decreased rectal temperature — that had previously been attributed to metabolic acclimatization (63). However, those same changes, which seem to imply a reduction in tissue insulation, are also characteristic of thin people as compared with fat people (64–66); and it thus seems possible that the changes attributed to training and acclimatization may in fact have been due, at least in part, to reduced fatness of the subjects, whose body weight and fatness were unfortunately not reported. This possibility is strengthened by Andersen & Wilson's finding (67) that when training produced a significant increase in fitness without a concomitant reduction in fatness the response of skin and rectal temperature to cold did not change, and the only effect was an increase in heat production.

The effect of physical training on responses to cold thus remains unclear. However, the available evidence seems to show that if training does have an effect it is in the direction of a reduction in tissue insulation. Hence a possible increase in fitness cannot explain the changes attributed to acclimatization in Antarctic wintering parties, since those changes have consistently indicated an increase in tissue insulation. Moreover, at Mawson in 1959 the observed changes in rectal temperature were unrelated to the subjects' estimates of changes in their physical fitness.

Summer expedition in wet-cold conditions

In 1963 six men were studied before and after six weeks of strenuous outdoor work in the wet and cold Antarctic climate of Heard Island (57). Exposure to cold, often in wet clothing, was frequent and sometimes severe. Three men experienced moderate hypothermia when they lost their survival equipment during a prolonged blizzard in the mountainous interior of the island, and one man's hands were frostbitten. All six men became significantly fitter ($P < 0.05$), as shown by the Harvard step test, and they became leaner, as shown by reduced body mass and skinfold thickness. Nevertheless their ability to tolerate a 2-h exposure to an ambient temperature of 4°C did not decrease, and they tended to shiver less. These findings suggest that enhanced vasoconstriction had compensated for the reduction in tissue insulation caused by the loss of fat (and perhaps by the increase in fitness). Additional evidence for this conclusion was that the finger cooled more rapidly and showed less cold-induced vasodilatation, and that significant changes observed in the arm-to-finger temperature gradient were consistent with increased countercurrent heat exchange in the forearm blood vessels. The results are thus fully consistent with those obtained with Antarctic wintering parties.

Laboratory acclimatization by cold baths

A successful attempt to preacclimatize expedition members before leaving Australia for Antarctica was made during the International Biomedical Expedition to the Antarctic (IBEA) (68; Budd et al, report in preparation). Six men were exposed for 2 h, nude, to an ambient temperature of 10°C before and after they had undergone 10 daily cold baths of a mean duration of 48 min in 15°C unstirred water. After the 10 baths they shivered less and produced 12 % less heat ($P < 0.01$) than beforehand, without incurring a significantly greater heat debt. The pattern and degree of the observed changes were the same as those associated with an additional 3- to 4-mm skinfold thickness, although the skinfold had not changed. The results imply that tissue insulation had increased as a result of enhanced vasoconstriction. A significantly higher rectal temperature in the first 30 min of the exposure was consistent with this interpretation. There was no evidence of nonshivering thermogenesis.

Concluding remarks

The eight Antarctic field studies differed widely as regards both the acclimatizing exposure and the test exposure, and the pattern of the subjects' responses was equally diverse. Nevertheless all showed statistically significant changes in men's responses to cold, and in every case the changes — whether an increased rectal temperature with an unchanged or reduced heat production, or a lesser heat production with an un-

changed heat debt — were consistent with an increase in tissue insulation. Horvath (69) has drawn essentially the same conclusion from a review of seasonal changes elsewhere. At the South African station SANAE the increased insulation was attributed mainly to fat deposition, but in most other Antarctic studies it appeared to be due to a more prompt, intense, and sustained vasoconstrictor response to cold. It is therefore concluded that general acclimatization to cold does indeed develop in the Antarctic.

Important negative findings of the Antarctic studies have been that (i) the changes produced by acclimatization differ from those that have been reported to accompany physical training, (ii) neither the resting metabolic rate nor the metabolic response to cold have increased, and (iii) there has been no evidence of non-shivering thermogenesis. The last two findings show that the mechanism of human acclimatization in the Antarctic differs from that of the acclimatized laboratory rat (2), even though the outcome — an improved defense of core temperature — is the same.

The findings of the laboratory study with cold baths confirm and extend those of Boutelier et al (70) and of Young et al (71), who also concluded that repeated cold baths induced an increase in tissue insulation. It seems remarkable that the violent shivering and hypothermia experienced in 10 cold baths should induce an adaptation of the same kind as that induced by normal life in Antarctica, where men are rarely cold enough to shiver or to sustain falls in deep body temperature (22, 29). That such different stimuli should produce a common adaptation of increased tissue insulation is perhaps analogous to the variety of response patterns in which that adaptation has been reflected. There would seem to be a need for further investigations, using techniques that provide more precise information about changes in tissue insulation and in the peripheral circulation.

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