

Third International Conference on Environmental Ergonomics

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Guest editor

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The problems associated with the thermal climate of the work environment, particularly those of temperature extremes, have multiplied in recent years. Efforts to reduce energy needs have increased the dissatisfaction of occupants with respect to the indoor climate of modern ventilated and air-conditioned spaces. The competition for natural resources has driven humans ever deeper into the earth and under the sea; they nowadays also work offshore or in the polar regions or in space. This rapid technological development has forced humans to live and work in climates differing radically from those in which they were biologically created. The result has been an increase in thermal strain during work and new health hazards.

Environmental ergonomics addresses the problems of sustaining the human ability to work under physiologically stressful conditions. The Third International Conference on Environmental Ergonomics was held in Helsinki, Finland, on 8–12 August 1988. It was planned and carried out through the cooperative efforts of the Finnish Institute of Occupational Health and the Foundation for Scientific and Industrial Research at the Norwegian Institute of Technology (SINTEF), and it was held under the auspices of the Finnish Ergonomics Society and the Nordic Ergonomics Society (NES).

The aim of the Conference was to bring together all professions associated with this field. Scientists, engineers, physicians, manufacturers, and representatives of governments and authorities were invited to present their recent findings and view points, to exchange opinions, and to outline needs for future research and development in the field of environmental ergonomics and in areas closely linked with it. The increasing number of participants from the beginning of this biennial conference series to its third meeting shows the need for maintaining such a forum now and also in the future.

The Helsinki Conference was structured around a number of worldknown specialists invited as keynote speakers for each main sessions. There were also submitted papers and posters. The first three days in Helsinki dealt with heat and cold stress, the effects of environmental stress on human physical and psychological performance, work and protective clothing, modeling and manikins, and standards and measuring methods. This period was followed by two days on board a ferry, where the special topic “Survival at Sea” was discussed.

It has been my pleasure to edit this supplement, which contains the keynote addresses of the first three days of the Conference. Two submitted manuscripts providing important information on the measurement of thermal radiation and the prediction of the wind-chill effect on work clothing have also been included.

I wish to express my warmest thanks to all the companies whose financial support made the organization of the Conference possible. Special thanks are due to all who took part in the Conference and made the program so very interesting. The publication of this supplement has been financially supported by the Finnish Work Environment Fund, which is gratefully acknowledged.

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CONTENTS

- 7 Evaluation of tolerance limits for humans under heat stress and the problems involved
HG Wenzel, C Mehnert, P Schwarzenau
- 15 Ergonomic aspects of cold stress and cold adaptation
GM Budd
- 27 Effects of thermal stress on human performance
AE Enander
- 34 Thermoregulatory models: recent research, current applications and future development
J Werner
- 47 Modification of Vernon's globe thermometer and its calibration in terms of physiological strain
HG Wenzel & A Forsthoff
- 52 Heat stress in protective clothing: interactions among physical and physiological factors
SA Nunneley
- 58 Recent trends in clothing physiology
I Holmér
- 66 The actual insulation of multilayer clothing
WA Lotens
- 76 Wind-chill equations predicting whole-body heat loss for a range of typical civilian outdoor clothing ensembles
DP Wyon
- 84 Use of thermal manikins in environmental ergonomics
DP Wyon

Evaluation of tolerance limits for humans under heat stress and the problems involved

by Hans G Wenzel, MD, Claus Mehnert, MD, Paul Schwarzenau¹

WENZEL HG, MEHNERT C, SCHWARZENAU P. Evaluation of tolerance limits for humans under heat stress and the problems involved. *Scand J Work Environ Health* 1989;15(suppl 1):7-14. Investigators are divided about the limits of tolerable ambient temperatures and air humidities, even under equal boundary conditions. In 266 climatic chamber experiments, mostly lasting 4 h, 13 young healthy men were exposed to combinations of ambient temperature (20 to 55°C) and relative humidity (5 to 97 %) at an air velocity of 0.3 m · s⁻¹. They were lightly clad and performed equal treadmill work (metabolic rate about 850 kJ · h⁻¹). Mean rectal isotherms and their standard deviations were calculated from the final rectal temperatures of the 13 men and plotted on a psychrometric chart. The slopes of the isotherms were compared with those of various "indices of heat stress." The probability of reaching the potentially critical rectal temperature of 39°C was calculated according to data of Wyndham & Heyns. It increased from about 1:500 000 to 1:150 in climates corresponding to mean isotherms of 37.6 and 38.2°C, respectively. Most of the limits thus far proposed are situated between these two isotherms, and they differ merely in regard to health risk. It is useless to discuss "correct" or "incorrect" limits until society has decided what risk is to be accepted. An upper tolerable limit per se does not and cannot exist. For several reasons the 37.6°C isotherm might be taken into consideration as a limit.

Key terms: criteria of heat tolerance, heat stress indices, individual health risk.

Climatic conditions above the thermally neutral, comfortable zone may produce unwanted effects on humans which can roughly be divided into three different groups (1). Relatively mild warm climates lead only to uncomfortable thermal sensations of warmth. Higher heat stress also results in a reduction of both physical and mental performance. Finally, if the conditions are severe enough and influence a person long enough, a person's health can be affected, and perhaps even death may ensue.

Although most warm climates cause only uncomfortable sensations in daily life and perhaps a decrease in work performance, one of the main questions asked in connection with heat stress is the limits tolerable in regard to the health of exposed persons. This question can be answered from the following two points of view: what maximum changes in physiological responses can be considered as being still harmless and what are the climatic limits corresponding to such harmless physiological changes?

In regard to the first question of limits, the predominant opinion is that conditions of thermal equilibrium are permissible. Heat accumulation is reflected by a continuous increase in body temperature and by an acceleration of heart rate. Thus heart rate may also be used as a criterion for distinguishing conditions of permissible heat strain from those potentially patho-

logical. In order to avoid continuous or frequently repeated measurement of responses under practical conditions, it is desirable to know what maximum levels of physiological responses can be considered safe. This knowledge is also important when thermal stress is very high but lasts only a short time. Most investigators describe rectal temperatures up to 38°C or slightly higher as being "acceptable" or "easy" or "safe," while temperatures around 39°C have been described as being "undesirable" or "excessive" or "unsafe" or "intolerable" (2-8). These values were derived in many laboratory experiments and field studies. They are particularly supported by Morrison & Wyndham's observations (9) on 314 heat stroke cases. Morrison and Wyndham found that a few deaths occurred at rectal temperatures of about 39 to 40°C on admission to the hospital. The probability of death increased significantly with increasing rectal temperature, reached 50 % at 42°C, and approached 100 % above about 45°C.

Several years ago, a working group of the World Health Organization also discussed the significance of heart rate elevations (10). The conclusion was reached that the degree to which both physical work and hot climate contribute to the actual heart rate has to be taken into account. Thus different values of maximum permissible heart rate, depending upon metabolic rate, have been recommended. Some investigators have also proposed limits in terms of sweat loss. For various reasons, however, it is doubtful whether this response can actually provide useful information (11-13).

If the body core temperature, or perhaps the heart rate, of humans exposed to hot climates is known, an evaluation is possible. However, practitioners often

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prefer limits in terms of stress instead of strain, in other words, limits of climatic conditions. They do so mainly for two reasons. Data on climatic elements can be obtained fairly easily because instruments for such measurements, and people trained to use them, are usually available when such evaluations are required, eg, in industrial plants. However, this situation does not always apply for the collection of physiological data. The second reason might even be more important. Knowledge of physiological data enables an evaluation only during exposure to heat. Often, however, it is necessary to predict effects before a person is exposed to a possibly dangerous climate. Such predictions can be made if the climate is known and previous experience with humans in comparable climates is available.

Many upper tolerance limits have been published for climates. They have been partly proposed or recommended in the scientific literature and partly established in official regulations, eg, for the mining industry in a number of countries (14–16). They usually take into account the fact that at least four climatic variables contribute to heat stress simultaneously, ie, temperature, velocity, humidity of the air, and radiant temperature. In addition two nonclimatic variables play an essential role, ie, metabolic heat production in the body and the thermal resistance of clothing. In this paper, interactions between all six of these main factors have not been discussed; instead attention is drawn to another aspect, which is based on principle. For this reason, the following data are restricted to certain conditions visible at first glance, and they are used for discussing only some questions on the tolerable limits of ambient temperature (air temperature equal to mean radiant temperature) and corresponding air humidity applying to equal additional conditions, ie, to a given metabolic rate, to a given clothing, and to a given air movement.

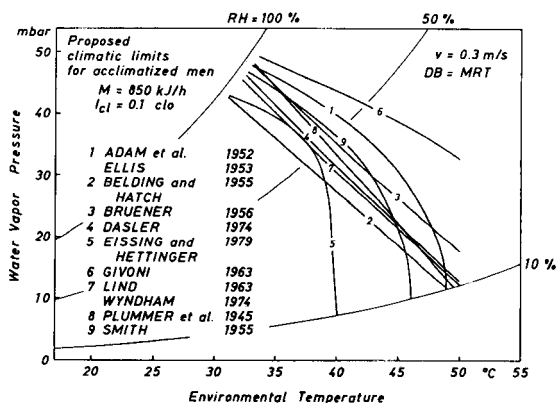


Figure 1. Climatic limits proposed for equal boundary conditions by various investigators (2, 3, 13, 17–24). (RH = relative humidity, v = air velocity, DB = dry bulb temperature, MRT = mean radiant temperature, M = metabolic rate, I_{cl} = thermal insulation of clothing)

One would expect that the limits proposed by various authors would be fairly similar. However, figure 1 proves that this is not the case. Such differences must irritate every practitioner. It should be mentioned that similar discrepancies appear when other values of the parameters are considered (25).

When the procedures for deriving the various limits presented in figure 1 are analyzed, some, but not all, of the reasons for the differences may be detected. Some limits, for instance, were based on practical experience collected in only a few climates. Others are results of more systematic studies in climatic chambers. When physiological measurements were made, different responses of the body were used as criteria, or different maximum values of the chosen criterion were applied. Furthermore, some limits were not derived from physiological investigations, but were instead calculated from heat balance equations. In such cases, sometimes different assumptions were made concerning the mean temperature, the wetness of the body surface, heat transfer coefficients, etc. Finally, it must be remembered that individual differences in heat tolerance are also reflected in the limits.

Subjects and methods

This situation induced us to start trying to answer some of the remaining questions with the use of a climatic chamber and the conditions presented in figure 1. A group of 13 young healthy men, acclimatized to heat, volunteered to participate, and 266 experiments, mostly walking up to 4 h on a treadmill, were conducted. We recorded rectal temperature, skin temperature at six sites, and heart rate continuously. Work was interrupted every 30 min for 3 min, during which body weight was measured. Ad libitum water intake, oxygen uptake, and carbon dioxide loss were taken into account in the calculations of extrarenal water loss. Respiratory measurements were made every hour. The experiments were always performed in the morning after about 1 h of rest in bed under thermally neutral conditions. The measuring methods have been described elsewhere (26).

Results

The arrangement of the climatic conditions of one of the series is presented in figure 2, showing the elevation of rectal temperature of one of the lightly clothed subjects at the end of work. Forty experiments were carried out in this series at ambient temperatures between 24 and 50°C and relative air humidities from about 10 to 95 %. The relationship between rectal temperature and climate was described by a mathematical equation (28), which is represented in the figure by the drawn curves. Although rectal temperature was not affected by air humidity at an ambient temperature of 24°C, it increased in very dry air as the am-

bient temperature increased, and it also increased in higher humidities at elevated temperatures.

It would now have been an easy step to transfer these results onto a psychrometric chart and to derive rectal isotherms, lines of equal rectal temperatures in relation to ambient temperature and air humidity. Diagrams similar to figure 2, however, were obtained from the respective results of other physiological responses measured in the same experiments. For this reason, we analyzed the relationships between the various responses first to make sure whether or not parametric influences existed. An example is given in figure 3. Our observations showed that equivalence lines plotted on psychrometric charts are identical when based on heart rate and rectal and mean skin temperature as shown in figure 4. It should be mentioned that a comparison of the measured values and those calculated as indicated by the curves resulted in correlation coefficients usually ranging from 0.90 to 0.95.

When the time courses of the aforementioned physiological responses were investigated, we found that, by the second hour of exposure at the earliest, either none of the responses had increased continuously (ie, they reached steady states under the relatively light conditions of the series) or they all continued to increase (under the heavier conditions). The "steady state limit" occurred at an average heart rate of 97 beats/min, a rectal temperature of nearly 37.8°C, and a mean skin surface temperature of nearly 36°C under the given work conditions (figure 4).

The next step was to analyze the behavior of weight loss, which corresponds approximately to sweat loss. Contrary to the results of figure 3, the relationship between body temperatures and heart rate, respectively, and weight loss was not independent of the combination of ambient temperature and air humidity (12, 29). Combinations of climatic conditions equivalent in regard to body temperature and heart rate were unequal to those found to be equivalent in regard to weight loss. Figure 4 shows climatic conditions of equal weight loss from 100 to 900 g · h⁻¹. This divergency between the behavior of sweat loss and the other responses was found in every series of experiments.

The existence of two equivalence systems raises the essential question of whether body temperature and heart rate or sweat loss should be used as the criterion for describing climatic conditions of equal heat stress. When figure 4 is examined, one obviously important consideration becomes apparent, ie, that the steady state limit is intersected by various lines of equal weight loss. This situation applies, for instance, to the curve of 500 g · h⁻¹ weight loss. Along this curve, thermal equilibrium was reached when the ambient temperature was about 40°C at relative humidities of up to 50 %, while heat accumulation occurred in higher humidities combined with lower temperatures. It seems to be a fundamental biological principle that conditions of thermal equilibrium on one hand and heat accumulation on the other cannot be regarded as being

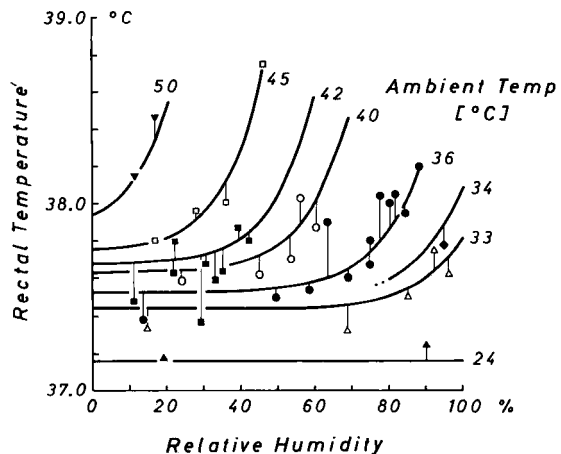


Figure 2. Rectal temperatures at the end of work in different ambient temperatures (Temp) and air humidities (subject OF, 40 experiments) (27).

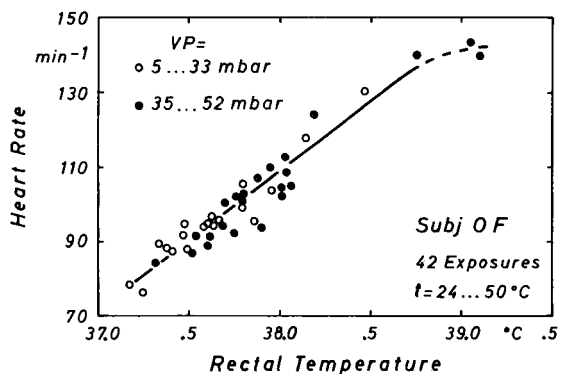


Figure 3. Relationship between final rectal temperature and heart rate (12). (VP = vapor pressure, subj = subject, t = temperature)

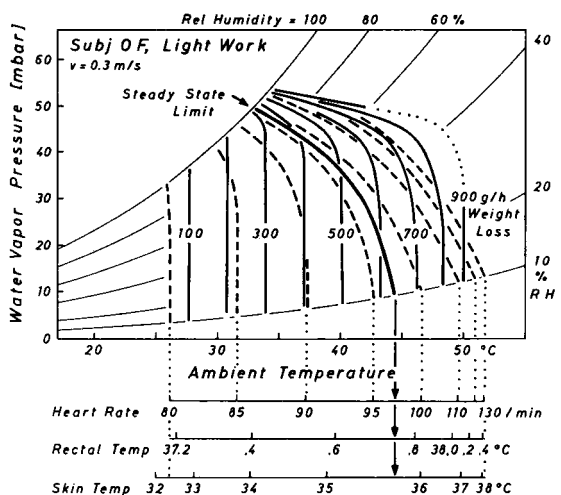


Figure 4. Equivalence lines derived from one of the experimental series (12). (Rel = relative, subj = subject, v = air velocity, RH = relative humidity, Temp = temperature)

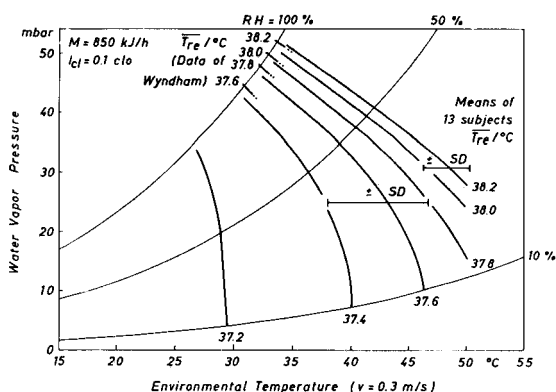


Figure 5. Mean rectal isotherms (SD 1.0) of 13 acclimatized young healthy men. (RH = relative humidity, M = metabolic rate, T_{re} = mean rectal temperature, I_{cl} = thermal insulation of clothing, v = air velocity, SD = standard deviation)

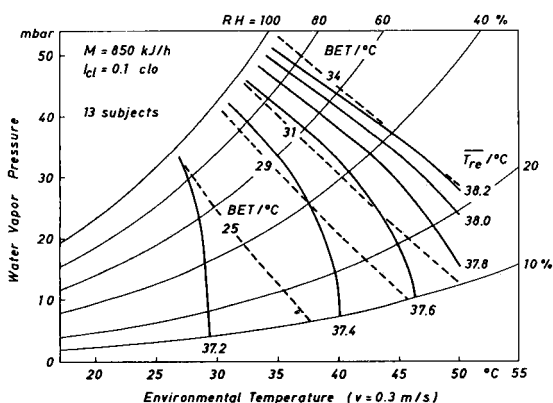


Figure 6. Lines of equal basic effective temperature (BET) (33) in comparison with mean rectal isotherms. (RH = relative humidity, M = metabolic rate, I_{cl} = thermal insulation of clothing, T_{re} = mean rectal temperature, v = air velocity)

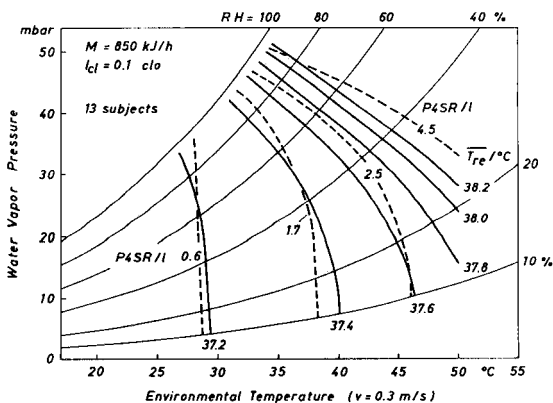


Figure 7. Lines of equal predicted 4-h sweat rates (P4SR) (35, 36) in comparison with mean rectal isotherms. (RH = relative humidity, M = metabolic rate, I_{cl} = thermal insulation of clothing, T_{re} = mean rectal temperature, v = air velocity)

equivalent merely because weight loss does not differ. Thus weight loss was excluded as a criterion, and the physiological responses mentioned first were used as the criteria of equal heat stress conditions.

The results of figure 4 were obtained with a single subject as an example. During the last several years about 50 similar series of experiments have been carried out in which the effects of various work levels (12), clothing ensembles (29), or air movements (30, 31) were also studied. In 13 of these 50 series, 13 different men served as test subjects under the same parametric conditions as in the series presented in figure 4. These 13 series enabled us to study interindividual differences and to derive mean rectal isotherms as shown in figure 5. The individual differences were considerable, as shown by the standard deviations, in spite of the fact that only young, healthy, seemingly equal men were investigated (32).

Figure 5 also shows data obtained by Wyndham (13), who seems to be the only investigator having carried out similarly comprehensive and comparable studies, although he restricted his experiments to climates with high humidity. It can be seen that both series of isotherms agree fairly well.

The derivation of mean rectal isotherms provides the opportunity for comment upon a fairly old question, namely, upon the extent to which various climatic indices actually describe physiologically equivalent climatic conditions. Together with the mean rectal isotherms, figure 6 shows the basic effective temperature (BET) (33), an index more than 60 years old, but still somewhat in use today. It can be seen that, under the conditions used, the BET overestimates air humidity under relatively mild heat conditions, but is nearly parallel to the mean rectal isotherm at 29 and 31 °C, except when the air humidity is low and the environmental temperature is correspondingly high. The same applies to still heavier climates corresponding to slightly higher effective temperatures.

It is not surprising that a very similar diagram results from a comparison of the mean rectal isotherms with curves of equal wet bulb globe temperatures (WBGT) (25). This index is frequently used, for instance by the National Institute for Occupational Safety and Health (34) in 1986, for describing "recommended heat stress exposure limits." This similarity goes back to the fact that, according to an unpublished notice of Yaglou, WBGT is nothing more than a "simplified version of the Effective Temperature Scale best suited to practical use in the field by personnel unskilled in psychrometry." The historical connection between the BET and WBGT is often unrecognized even though Yaglou participated in the development of both these indices.

Figure 7 demonstrates lines of equal values of the predicted 4-h sweat rate (P4SR) index (35, 36). Contrary to slopes of the BET in figure 6 the P4SR values coincide fairly well with the rectal isotherms, particularly in the range of mild and medium climates. The systematic intersections of the isotherms correspond

to the results shown in figure 4. These comparisons have been restricted to only a few indices even though others might also be of interest. However, the question of heat indices will be taken up again in the discussion of another aspect of the findings.

Now let us reconsider the different upper tolerable limits proposed by various authors (figure 1). Figure 8 demonstrates the whole climatic range in which these limits are situated. In addition, the mean rectal isotherms have been inserted. Although rectal temperatures up to about 38.2°C are usually tolerable, the mean rectal isotherm of 38.2°C must probably not be considered as a tolerance limit applicable to a greater population. Because of individual differences in heat tolerance, it has to be expected that, under the climatic conditions described by the mean isotherm of 38.2°C in figure 8, less heat tolerant men will reach higher rectal temperatures and, therefore, may be endangered.

Discussion

The fact that some subjects will always reach higher rectal temperatures leads to the question of the actual health risk of a greater population in climates described by various mean isotherms. It was not possible to answer this question from the results of the climatic chamber experiments that have been presented in this report. For safety reasons the exposure time was usually shortened if the rectal temperature of the respective test subject exceeded the "safe" level of about 38.3°C. "Potentially critical" rectal temperatures near or above 39°C were reached by the subjects in only a few experiments. More daring studies have been carried out, however, by other investigators (8, 13, 38). Wyndham (13) and his co-workers exposed men to severe conditions of work and ambient climate producing rectal temperatures of 39°C or higher in a number of cases. They derived distribution curves of rectal temperatures applying to greater groups of subjects. Using these data, they calculated mean rectal temperatures on one hand and the risk of reaching various temperatures above the mean values on the other. As shown in figure 5, the mean values worked out by Wyndham and the corresponding mean rectal isotherms agreed very well. For this reason, it seemed justified to make use of Wyndham's data, indicating how often higher rectal temperatures are observed. They demonstrated that under climatic conditions producing the "safe" rectal temperature of 38.2°C on an average, the rectal temperature of one man out of 150 can be expected to reach 39°C (figure 8).

In fact the very point at which the various proposed limits of figure 1 differ from each other can be seen in figure 8 as the conditions under which the risk is 1:500 000 (37.6°C isotherm). For many years, discussions have been under way about which proposed limits are "too high" or "too low." Such discussions are useless, as the suppositions necessary for answering this

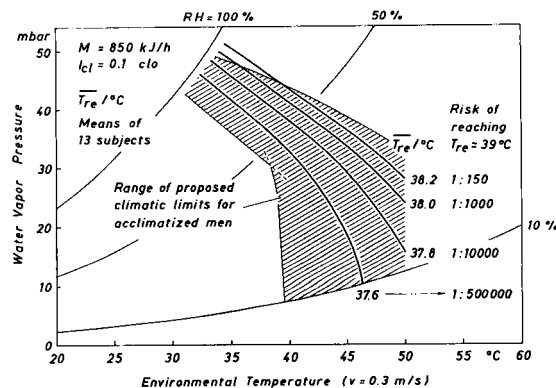


Figure 8. Range of proposed climatic limits (from figure 1), mean rectal isotherms (from figure 5) and risk of reaching a rectal temperature of 39°C according to Wyndham & Heyns (37). (RH = relative humidity, M = metabolic rate, I_{cl} = thermal insulation of clothing, T_{re} = mean rectal temperature)

question are still missing. It is first necessary to answer the essential question of what particular health risk should be accepted. However, the answer to this question has, in the end, to be provided politically. It is certainly a medical task to evaluate data of risk, but it is doubtful whether the answer should be expected from the field of medicine. It has to be realized that an upper tolerance limit per se does not and cannot exist. Data like those presented in this report permit permissible environmental conditions to be specified, but only after society has decided what health risk is to be accepted.

In spite of his great experience with heat stress, Wyndham abstained from making this decision. There seem to be only two very careful remarks in his publications that one might perhaps take into consideration, a climatic limit which — under the parametric conditions already mentioned — would be situated in the range of the mean rectal isotherm of 37.6°C (ie, the level at which the risk of a potentially critical rectal temperature of 39°C being reached is 1:500 000). The proposals — partly higher, partly lower — of some authors were formulated in a more apodictic way. Others, however, have formulated their proposals fairly carefully and with certain reservations.

The next obvious step is to compare the various proposals with particular reference to the 37.6°C isotherm and, in addition, to its relatively large standard deviation. This comparison is shown in figure 9. The diagram shows that the majority of the proposed limits are situated fairly close to the isotherm, at least within the hatched range of individual variability of the 13 subjects. Only a few exceptions exist. The highest limit, proposed by Givoni (21), corresponds roughly to the mean rectal isotherm of 38.2°C, which is not plotted in figure 9. When developing his "index of thermal stress," Givoni calculated this curve for describing climatic conditions producing a sweat rate of 1100 g · h⁻¹, which he considered "as the upper limit under prolonged exposure for healthy and ac-

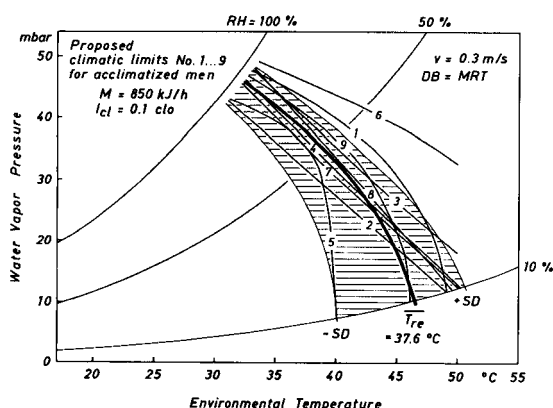


Figure 9. The 37.6°C rectal isotherm (thick solid line) in comparison with the proposed climatic limits of figure 1. (Hatched range of climate = 1.0 SD, 1 = Adam et al and Ellis, 2 = Belding & Hatch, 3 = Bruener, 4 = Dasler, 5 = Eissing & Hettinger, 6 = Givoni, 7 = Lind and Wyndham, 8 = Plummer et al, 9 = Smith)

climatized men [p 8].” He found in his experiments that “when average weight loss was approximately 1100 g/h, rectal temperature was 38.3°C [p 3].” His calculation of the mean curve was fairly correct. However, he did not consider the risk of reaching rectal temperatures above 38.3°C, in particular the possibly critical temperature of 39°C.

The limit of Adam et al (17) and Ellis (20) corresponds to a P4SR of 3.0 l. It is situated slightly above the upper range of the standard deviation of the isotherm in figure 9. On the other hand, the lower part of Eissing & Hettinger's limit (19) approaches the lower range of this standard deviation. It is based on calculations of the so-called "required sweat rate" by Vogt et al (39, 40).

The limit proposed by Lind (22) and Wyndham (13), corresponding to Wyndham's proposal of an effective temperature of 31°C, is similar to that of Dasler (3) (WBGT = 32°C). Both these limits coincide with the 37.6°C isotherm at high air humidities, but deviations occur for dry and correspondingly hot climates. It has to be remembered, however, that the studies of Wyndham were restricted to the climatic conditions of South African gold mines, which are characterized by high humidity.

If one considers the standard deviation of the isotherm presented in figure 9 generously, the conclusion could be reached that neither most of the limits proposed nor the indices differ extremely. However, the slopes of the limits could be analyzed more in detail. Some of the limits are linear or nearly linear, while others are curved. Although nearly all of the limits are situated within the area of the standard deviations, the differences should not be underestimated. As already mentioned, exposures to climates of this range generally result in a relatively small health risk. However, the risk for conditions in the upper part of the standard deviation range may be about a hundredfold of the risk for conditions in the lower part. Thus a con-

siderable increase of risk with increasing ambient temperature would apply to those limits which are linear and relatively flat, for instance, the limit of Belding & Hatch (18).

Numerous results from systematic physiological studies on humans have indicated that physiological equivalence is nonlinear, ie, is slightly curved in this range of climate. One of the oldest of these studies (41) was published in 1945. Under these circumstances, linear equivalence lines or — in the present case — linear limits can be suspected to contain errors or simplifications.

On the other hand, the limits of Adam et al (17) and Ellis (20), Eissing & Hettinger (19), and Smith (24) are more curved than the isotherm. They are the very limits with sweat rate as the criterion. It has already been pointed out that there are two opinions about the question of whether this response is a suitable criterion for describing climatic conditions producing equal heat stress. For this reason, a line only slightly curved, like the 37.6°C isotherm, can be suggested as an equivalence line. Whether this isotherm is considered simultaneously as the upper tolerance limit under the parametric conditions discussed, however, depends upon the pivotal question of whether the corresponding health risk will be accepted by society.

Concluding remarks

The heat stress conditions chosen as an example for this survey are easily visible at first glance. However only two of the six main factors contributing to heat stress were considered, ambient temperature and air humidity. Nevertheless, even this simple example shows that the evaluation of an upper tolerable limit includes several problems. The first is the divergency of the different limits proposed previously by various authors. This divergency led to the question of which physiological responses of humans under heat stress can be used as criteria for describing tolerable conditions. Carrying out a total of about 1000 whole-day climatic chamber experiments over a number of years produced another problem in so far as much patience was required of all those concerned, ie, both the investigators and the test subjects. The results obtained made it possible, however, to touch the old problem of the reliability of various heat stress indices.

The fact that 13 subjects were studied under comparable conditions proved the importance of individual differences for any statements about tolerance limits. The results proved that an upper tolerance limit *per se* does not exist and that the essential problem is to obtain the inevitable decision of society on what health risk should be accepted. One observation was made which might be helpful to those involved in this work. The range of climate in which most of the various diverging limits proposed in the past are situated is similar to the range of climate corresponding to the individual variability of the 13 subjects who volun-

teered for the described experiments. The survey may offer some information with which to obtain an answer to the question under discussion.

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Ergonomic aspects of cold stress and cold adaptation

by Grahame M Budd, MD¹

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?

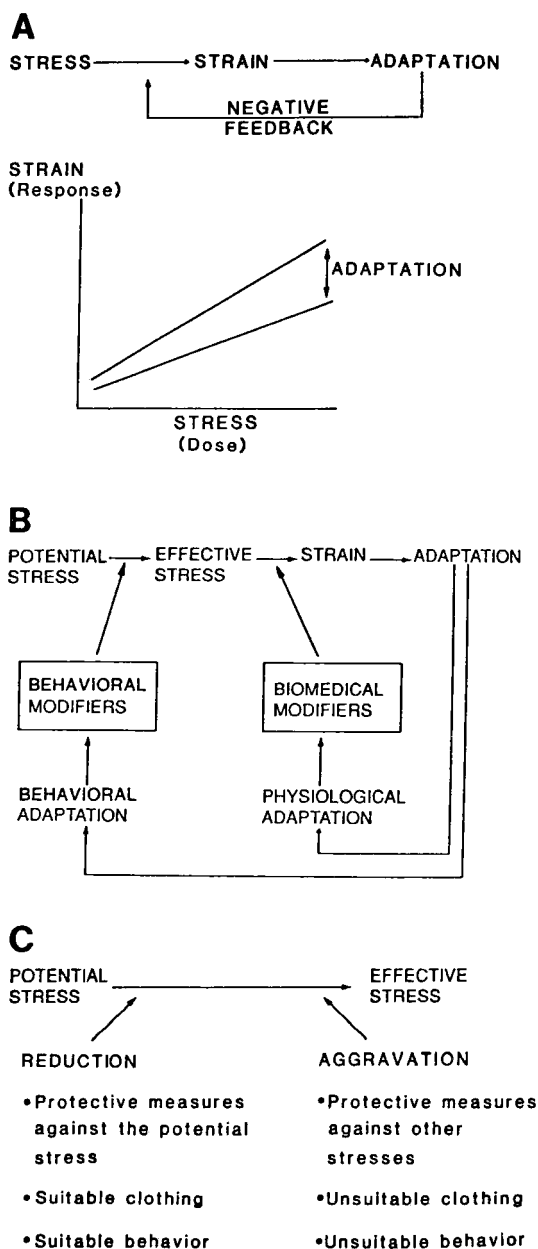


Figure 1. Stress, strain, and adaptation: the basic idea (A), possible complications (B), and the behavioral modifiers (C).

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

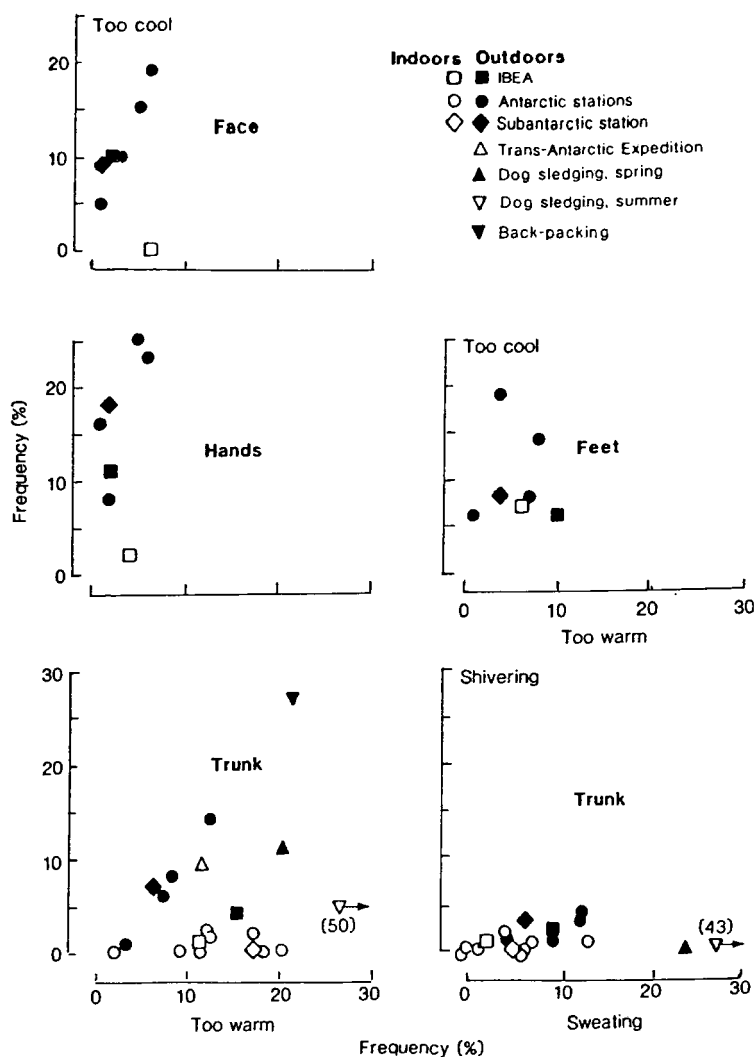


Figure 2. Thermal discomfort indoors and outdoors. Each point is the average of all the observations made on one expedition or journey. The data are from references 22, 24—29. [IBEA = a snowmobile trip during the International Biomedical Expedition to the Antarctic (28)] [Reproduced, with permission,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

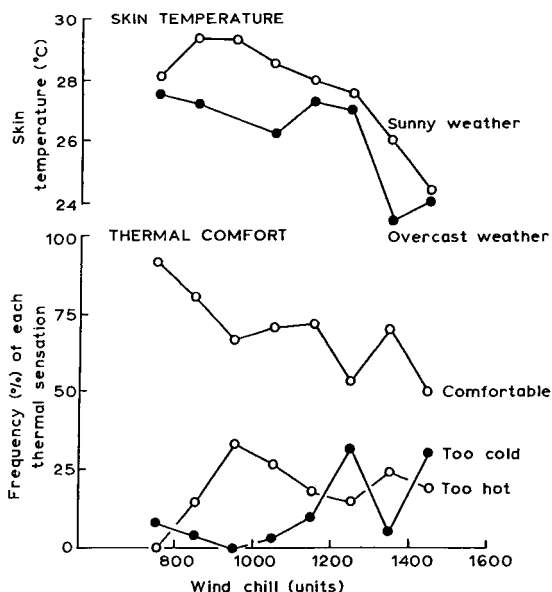


Figure 3. Effects of thermal environment on men traveling by dog sledge in spring — skin temperature of the medial thigh, and the distribution of thermal discomfort, in each class interval of wind chill. [Reproduced, with permission, from reference 26]

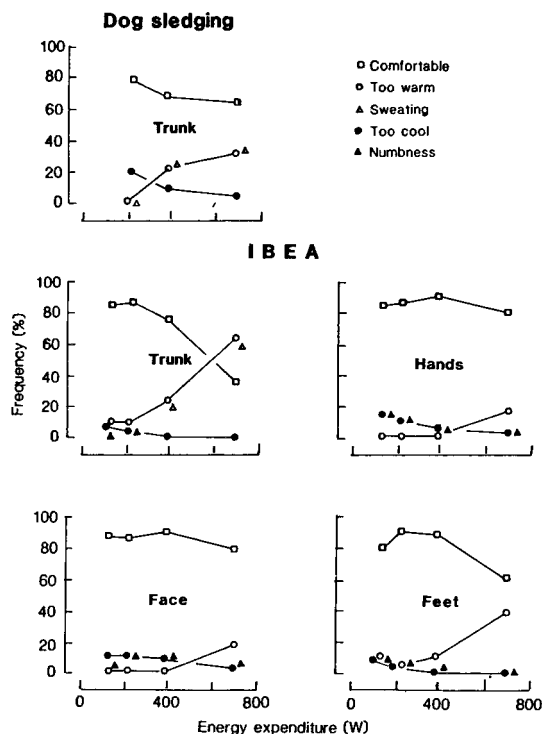


Figure 4. Effects of activity on men traveling by dogsledge and by snowmobile in similar thermal environments — the distribution of thermal discomfort outdoors at each grade of work. The distribution of cold-induced pain, omitted for clarity, was similar to that for numbness. The data for dog sledging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

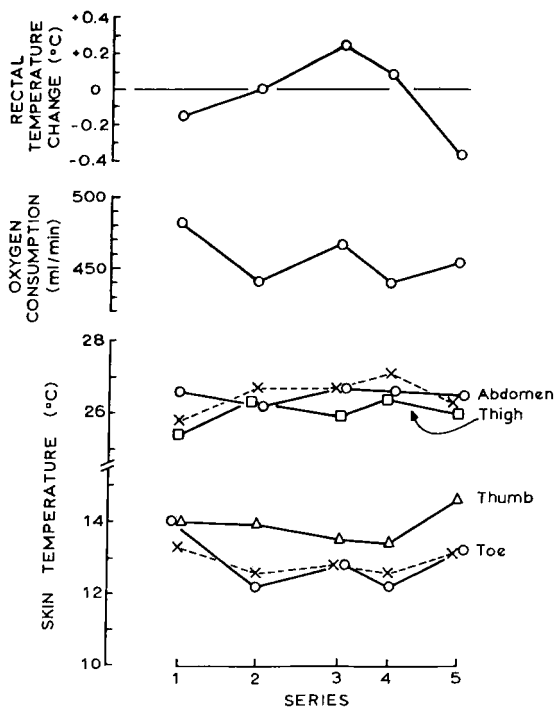


Figure 6. Responses of body temperature and oxygen consumption to cold — mean values of the eight exposures made in each of the five series of nude exposure experiments of the Mawson 1959 expedition. The distance between the series is proportional to time. The observed skin temperatures of the abdomen 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]

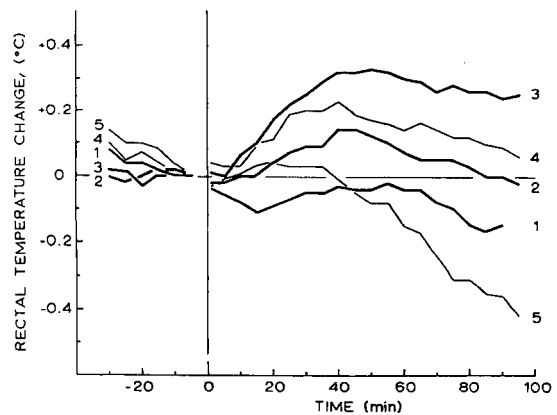


Figure 5. Rectal temperature change — mean values of the eight exposures made in each of the five series (shown by their respective numbers) of nude exposure experiments of the Mawson 1959 expedition. Zero time indicates commencement of the test cold exposure. [Reproduced, with permission, from reference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

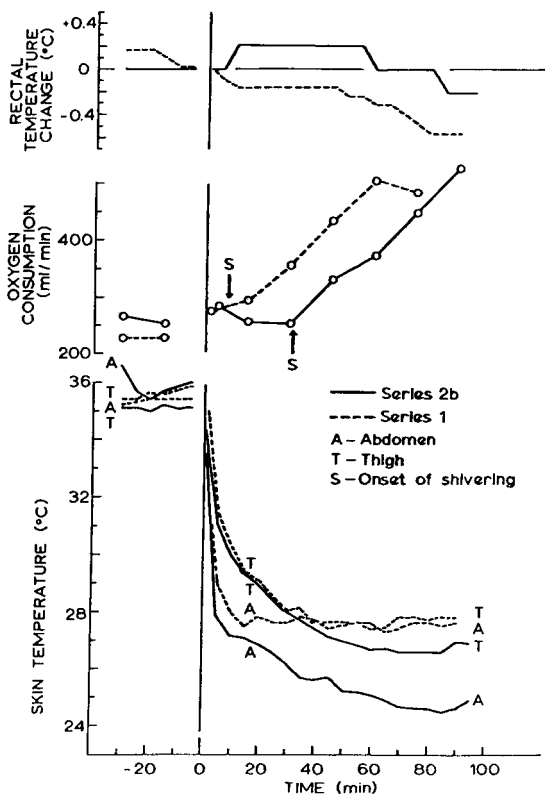


Figure 7. Body temperature, oxygen consumption, and onset of shivering of one subject in the second exposure of series 2 of the nude exposure experiments of the Mawson 1959 expedition, in comparison with his mean values in series 1. (Zero time = commencement of cold exposure) [Reproduced, with permission,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

bly 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

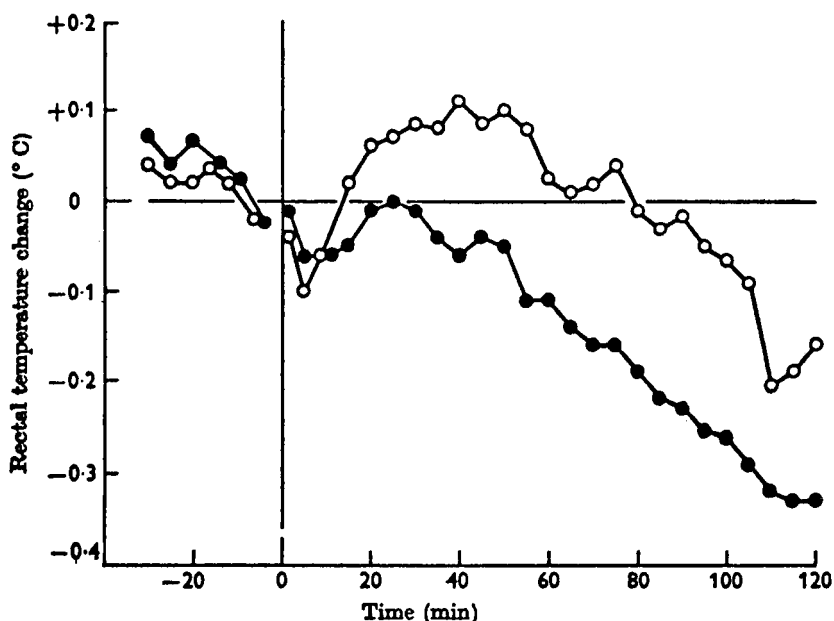


Figure 8. Rectal temperature change in Melbourne (filled circles) and Mawson (unfilled circles) — mean values of the eight exposures made in each series of the nude exposure experiments of the Mawson 1964 expedition. (Zero time = commencement of cold exposure) [Reproduced, with permission, from reference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

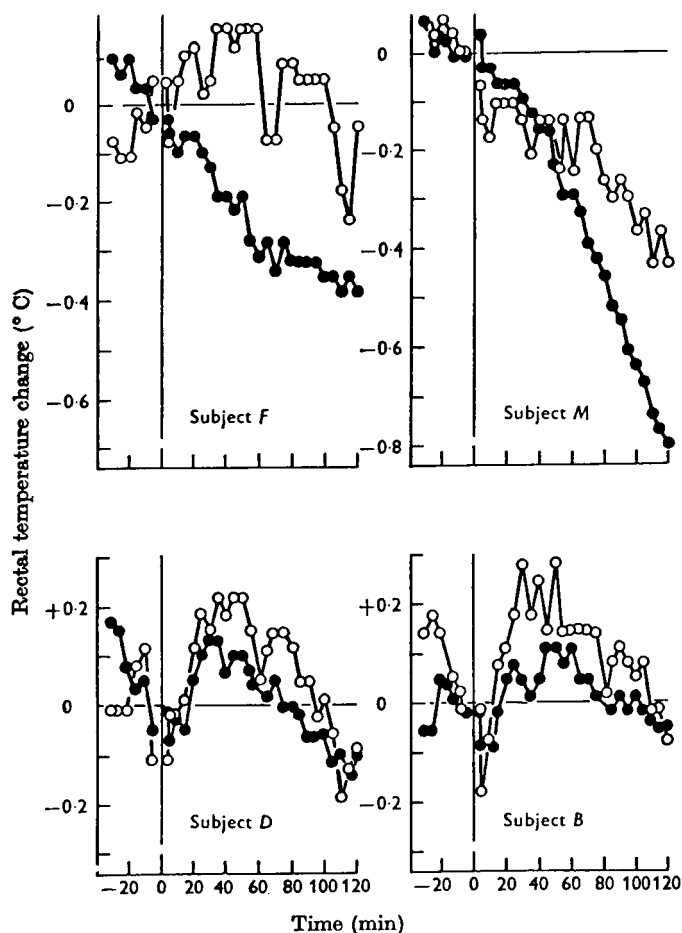


Figure 9. Rectal temperature change in Melbourne (filled circles) and Mawson (unfilled circles) — individual values (mean of two replicates) in each series of the nude exposure experiments of the Mawson 1964 expedition. (Zero time = commencement of cold exposure) [Reproduced, with permission, from reference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

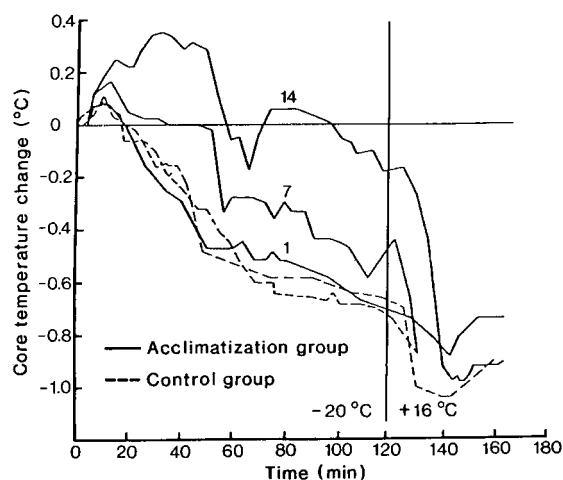


Figure 10. Core temperature change during clothed cold exposures and subsequent rewarming at Halley Bay in 1968 — mean values on the first, seventh, and fourteenth day (shown by their respective numbers) of artificial acclimatization. (Zero time = commencement of cold exposure) [Reproduced, with permission,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

by Ann E Enander, PhD¹

ENANDER AE. Effects of thermal stress on human performance. *Scand J Work Environ Health* 1989;15(suppl 1):27—33. Experimental evidence indicates that even relatively mild thermal stress may affect human performance. Tasks requiring manual dexterity and muscular strength are clearly impaired by cold exposure, while decrements in vigilance performance and endurance are well documented effects of heat stress. The considerable variation in results regarding the effects of thermal stress may, to some extent, be attributable to complex interactions between exposure conditions, task characteristics, and individual factors. In the present paper the relevance of some of the earlier research work on heat and cold stress is evaluated in the light of the practical and theoretical implications of more recent findings. Current work regarding the nature and extent of the effects of thermal stress on more complex performance is discussed. Attention is also focused on the significance of individual skill and training experience for performance under unfavorable conditions.

Key terms: cold, heat, manual performance, mental performance, physiological reactions, skill, training, vigilance.

Despite advances in technology and protective equipment, people are still required to carry out a wide range of activities under different forms of thermal stress, often in combination with other stressors such as, eg, noise. While the limits of endurance are seldom put to the test in the work environment today, thermal stress can be linked to a wide variety of unfavorable effects, including an increase in unsafe work behavior (1).

Performance measures have increasingly come to be applied in evaluating the effects of environmental stress from both physical and chemical agents (2). The significance of effects on performance can be discussed in a number of different terms, for example, as factors affecting productivity, as potential safety hazards, as factors increasing the physical or subjective cost of effort, or as indicators of a biological effect with possible longer-term consequences for health.

With a historical perspective of the research on thermal stress, it is possible to discern an ebb and flow of work around certain issues. These concentration areas reflect a pragmatic approach to resolving questions of practical importance in applied situations, and the theoretical development has held a lower profile. The unsystematic nature of the work has also created problems in interpreting the results, a fact which has been commented on by several reviewers (3—5). Differences in the methodology used, the definition of thermal stress, and performance measures have contributed to this confusion.

Nevertheless, in more recent work it is possible to discern a phase which might be characterized as one

of reevaluation. There appears to be a revival of interest in some of the stagnated issues regarding the performance effects of thermal stress, and this revival is providing a fresh impetus both in theoretical discussions and in practical applications. One such approach can be noted in the application of theoretical developments from adjacent fields of environmental stress research. This phenomenon can be exemplified by the current reevaluation and discussion of the arousal theory. During one period individual differences were mainly regarded as an unfortunate confounding factor. There now appears to be an increased interest in these differences, particularly in relation to skill, experience, and training.

It is the purpose of this paper to discuss some of the basic issues regarding research on performance during exposure to thermal stress and to consider the current view of effects of cold and heat from the perspective of more recent developments.

How are performance effects related to thermal stress?

One of the basic problems in this research area is that of establishing a relevant measure of thermal stress to which performance effects can be related. Exposure to thermal stress has, for example, been achieved by means of varying air temperature, wind speeds, or physical work or of submerging the body in cold or warm water. The pattern of physiological reactions differs according to the means applied and makes a comparison of the results obtained in different studies difficult. While an environmental stressor such as a noise, defined in physical terms, can at least be regarded as an equivalent stimulus in different studies, situations, and groups of people of normal hearing, the same cannot be said of a certain thermal environ-

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ment. The impact of a thermal environment may, for example, vary according to a number of individual characteristics of the subjects, such as age, sex, fitness, etc. Physiological measures provide a more accurate indication of the thermal stress on the individual. Some physical and motor performance criteria appear to be relatively well related to physiological changes. The temperature of the hands, for example, is clearly a limiting factor in the performance of manual tasks in the cold (5, 6).

It has proved more difficult to establish relationships between physiological measures of thermal stress and mental performance. This situation is hardly surprising, since performance on more complex cognitive tasks is the result of an integration of physiological reactions, physical and mental capabilities, and subjective assessments. Thus, while it is, for example, clear that heat stress affects the level of performance on tasks requiring vigilance and sustained attention, the exact nature of the effects has been difficult to ascertain. Although early work indicated a pattern of decrement, later studies have also demonstrated little change (7) or even improvement (8, 9) in performance. A survey of these varied results can be found in a number of reviews on the effects of heat (3, 10, 11). In contrast, the effects of cold on complex mental tasks have received less attention. This lack of interest has variously been attributed to the fact that technology and protective devices have rendered such effects of academic rather than practical significance or that effects of cold may be dismissed as being negligible under less drastic cooling conditions or possibly attributable largely to confounding between mental and manual effects (3, 12).

Two main theoretical approaches have traditionally been favored to explain the effects of thermal stress on complex performance. The classic inverted-U arousal theory hypothesizes an optimal level of arousal for performance of a certain type of task. In principle, a simple task may be facilitated by an increase in arousal, while the optimal level of arousal is lower if the nature of the task is more demanding. An environmental stressor which is hypothesized to increase the level of arousal could be expected to facilitate performance on, eg, vigilance tasks, while causing decrements on more complex tasks. However, in order to accommodate the varied effects of stress on performance, an increasingly elaborate interaction between individual characteristics, task properties, and arousal patterns has been hypothesized (8). While this line of reasoning has significantly contributed to the comprehension of the nature of stress effects, in particular their ability also to improve performance, the serious limitations of indiscriminately using arousal explanations have recently been pointed out by several authors [eg, Bell & Greene (3) and Hockey & Hamilton (13)].

The traditional alternative theory involves the concept of the stressor as a distractor. An early hypothesis (14) proposed that performance is affected nega-

tively when attention is directed away from the task by distracting environmental stimuli. Clearly this theory also encounters difficulties, eg, in explaining an improvement in performance under stress.

More recently there have been developments which may help break the circularity of the arousal-distraction discussion. One is the increased use of more sensitive test and analysis methods that enable researchers to study not only increments and decrements in one total performance measure, but also more subtle changes in, eg, performance strategy. There has also been a shift in emphasis towards describing performance effects in terms of patterns of bodily and cognitive changes rather than in terms of unidimensional arousal-distraction patterns. The development of this approach has been extensively discussed by Hockey & Hamilton (13) as applied to different stress states, such as noise, monotony, etc. In this connection Hockey & Hamilton point out the ambiguity of the heat stress state and do not enter into any discussion of the possible cold stress state. It is beyond the scope of this paper, or indeed of the status of present research results, to fill this gap. The following brief look at recent work does however indicate (i) that effects of cold stress on complex performance, while elusive, may not be negligible and (ii) that a more comprehensive view of the effects of heat is emerging.

Performance during cold exposure

The general effect of cold on the performance of physical and motor tasks is one of impairment. A reduction in core body temperature and muscle temperature generally reduces physical function in a number of ways, eg, muscle strength, duration of exercise, etc (12, 15). The specific effects of cold on the functioning of the hands has been the subject of particular interest. This focus reflects the widely documented problems encountered in attempts to protect the hands from cooling while maintaining unimpaired dexterity (16). Early work indicated that it is the temperature of the hands which is critical for manual performance (17, 18), although severe body cooling and shivering can also affect the performance of some tasks (19, 20). Considerable research has been devoted to establishing the range of temperatures within which performance remains unimpaired. Critical hand and finger skin temperatures have been found for unimpaired tactile sensitivity at 8–10°C (21, 22) and for manual dexterity at skin temperatures of 12–15°C (23, 24).

While the direct relationship between cooling of the hands and a progressive decrement in manual performance is well established, the actual degree of impairment is subject to a number of task and cooling factors. Clearly, tasks involving fine movements of the fingers and hands or the manipulation of small objects are particularly sensitive to the effects of cold (25, 26). Slow cooling, as found in many occupational settings,

is more detrimental to manual performance than rapid cooling to equivalent hand skin temperatures (27, 28). The progressive development of more sensitive techniques of measurement and analysis may tend to result in effects being found at increasingly mild levels of cooling (29, 30).

Research on the effects of cold on more complex tasks has, as has already been pointed out, been meager. A study of shipboard lookouts by Poulton et al (31) is often cited as indicating effects of cold on vigilance, although the interpretation of the results was complicated by confounding wind and rain under the control conditions.

Interest in the effects of cold on complex mental functions has been stimulated by several studies of divers working in cold water. The discussion as to the applicability of these results to other forms of cold exposure being laid aside, this work has shown effects of cold on a number of complex tests (32, 33). Support for the concept of cold as a distractor is found in a study of divers exposed to cool (15.5°C) and cold (4.5°C) water conditions (34). The results from this study showed that performance on two complex tasks was significantly poorer in the cold water only during the first of the 3 h of exposure. During the second and third hours of exposure performance did not differ between the cold and moderate water temperatures, in spite of increasing differences in the degree of physiological cooling between the two conditions. The results during the first hour were attributed to the greater distracting effect of the cold environment, an effect independent of deep body cooling.

Two studies of cold air exposure (35, 36) demonstrated an increase in errors on a serial choice-reaction time test, but no increase in the number of lags registered. Increasing the complexity of the choice in the test (36) led to a relative increase in errors made in the cold. Taken together, the results of these two studies were interpreted in terms of the arousal theory. The increase in errors was hypothesized to result from a change in strategy caused by a cold-induced increase in cortical arousal.

Recent work (37) has demonstrated significant increases in the number of errors, speed of incorrect response, and number of false alarms on two computerized tests during mild cold exposure of a group of women. These effects were only obtained in tests designed to require continuous rapid accurate responding with minimal opportunity to inhibit erroneous reactions. It is interesting to note that an increase in rapid errors on a serial choice-reaction time task was recently reported at lower levels of noise than noted previously. This result was obtained following a task modification to minimize hand movement, and thereby the response latency and the time allowed for correcting erroneous reactions was also decreased (38, 39). An increased number of responses to blank trials during cold exposure, previously noted in flicker-fusion threshold determination (40), may be interpreted as

demonstrating a similar effect of erroneous response. Thus there is evidence that at least one effect in the possible pattern of cold stress might be a decreased ability to inhibit erroneous responses.

Performance during heat exposure

The general relationship between physiological changes in response to heat stress and physical performance is held to be relatively clear and predictable. There is little initial effect on physical strength, but the gradual accumulation of heat in the body during longer and more intense exposures gradually builds up fatigue and a corresponding decrease in endurance. The importance of the time factor is reflected also in the discussion of applicable limits for mental and psychomotor tasks of various kinds (10, 41, 42).

Many of the studies investigating the more complex effects of heat have used tasks involving sustained attention and vigilance. There is evidence of a nonlinear relationship between a rise in body temperature and performance. Mild heat exposure appears to impair performance on vigilance tasks, while further heat stress may induce improvement. For more complex mental tasks the effect is the reverse, initial facilitation followed by impairment. The overall picture is, however, confusing since the effects may vary according to factors such as the duration and severity of exposure, the characteristics of the task, and the characteristics of the individual. A complex pattern of arousal has been proposed to account for these effects, invoking an initial stimulating effect, followed by a sequence of decreased arousal associated with adaptation, increased arousal in response to rising body temperature, and a final decrease as exhaustion is approached (8). In view of the lack of reliable independent measures of arousal this theory, while elegant, is clearly open to criticism in view of its post hoc nature.

Recently Hancock has conducted comprehensive reanalyses of the work on sustained attention under heat stress in relation to body temperature changes (11, 43, 44). He makes a clear distinction between conditions under which body temperature is undergoing a dynamic increase and those under which body temperature is unchanged or established in a static hyperthermic state. According to Hancock's analysis, dynamic temperature change is associated with performance decrement, while subjects in a stable state show no change or even improvement in performance. While emphasizing the descriptive rather than explanatory nature of this relationship, Hancock points out the practical applications if inertial intervals during which body temperature remains stable can be used to calculate safe tolerance periods for tasks requiring sustained attention (44).

One reason for the apparent disparity in results regarding heat stress may lie in the use of the general

term "heat stress" to cover a variety of different stress states. Closer attention to both the level and direction of physiological reactions may help clarify the picture. This approach is also strongly advocated by Allan and his associates (45) on the basis of a series of experiments indicating that direction and rate of change in both core and skin temperatures may be important determinants of performance.

Effects of thermal stress in relation to training and skill

Given that, in some cases, the possibilities of modifying the environment or the task are limited, a central question is whether people can be trained to withstand the negative effects of that environment. While physiological acclimatization to heat is a widely accepted phenomenon and may increase the capacity for physical work, the evidence of a corresponding improvement in psychological performance is ambiguous (9). The position as regards cold exposure is still less clear-cut and has been widely debated. While local acclimatization effects, in the form of increased finger temperature and rapid onset of cold-induced vasodilatation, have been found among habitually cold-exposed subjects (46—49), the relationship between such effects and performance has not always been clear (50). Conversely, while instances of improved manual performance have been demonstrated among subjects familiar with cold exposure, concomitant physiological changes have not necessarily been established (51).

Irrespective of the existence of physiological changes in response to repeated exposure to thermal stress, the general view seems to be that familiarity breeds, if not contempt, then at least competence. This view would seem to imply the concept of the stressor as a distractor. With increased familiarity the impact of distracting stimuli, which divert attention from the task at hand, should decrease.

There are indications that subjects accustomed to cold exposure experience less discomfort than unaccustomed subjects at equivalent skin temperatures. In a study of reactions to local hand cooling (52), meatcutters and office workers were compared with regard to physiological and psychological responses during both cold stimulation and a passive recovery phase. No differences were found between the groups as regards hand skin temperature measurements, but the meatcutters were found to experience significantly less cold and discomfort particularly under the conditions in which room temperature was set at 10°C, the normal work environment temperature of the meatcutters. This result might be interpreted as indicating a decreased impact of situation-specific sensory stimuli among the accustomed workers. Similar results have been obtained in heat exposure (53). However, a direct connection between reduced discomfort and im-

proved performance is not self-evident. Indeed, it might be suggested that a reduction in discomfort with no equivalent reduction in physiological reaction may in fact constitute a hazard as regards decreased sensitivity to significant sensory warning signals.

There is also a general view that practice under thermal stress enables the individual to develop a more adequate behavior pattern. The positive effects of training in the cold are often cited, generally with reference to an early study by Clark & Jones (54). In this study manual performance during cold exposure was studied as a function of the thermal conditions of training. Briefly the results indicated that a change in thermal conditions after a period of practice resulted in a relatively greater decrement in performance, irrespective of the direction of the change. Thus subjects who learned the task under neutral conditions performed worse under cold conditions than subjects who had experienced cold during the practice sessions. The data also indicated that subjects training under cold conditions were inferior to comparison groups when tested under neutral conditions. The authors stressed the importance of varied thermal experience early in training and suggested that the thermal conditions under which a task is performed may become part of the stimulus complex to which the correct manual response is connected over a period of training. Consequently any change in these thermal conditions causes a disruption in performance.

More recently there has been a revival of interest in the possible effects of training on performance. I recently conducted a study of manual performance training in a group of women unfamiliar with manual work or cold exposure (55). The results differed to some extent from those of Clark & Jones, since they do not indicate any advantage of practice under cold conditions for subsequent performance in the cold. Indeed, practice under neutral conditions tended to be more advantageous for a task involving complex manual manipulations, in this case a screw manual dexterity task. It should be noted that in my experiment the group was female and completely untrained, while in the formerly cited study the group was made up of male military personnel, presumably relatively skilled in manual work, who also had some opportunity for practice with warm hands. A recent study (56) of relatively inexperienced male military personnel practicing manual tasks under different thermal conditions also revealed results resembling those of my study. When tested in the cold, the group who had practiced under normal thermal conditions was found to perform somewhat better than the group who had practiced in the cold.

Learning to perform a task in the cold may thus be less advantageous. However, a study of visuomotor performance (57) indicated that cold affects the level of performance rather than learning, since rapid recovery to the expected practice level was found on returning to warm conditions. Differences in the type of task,

or again in level of skill, may contribute to the conflicting evidence. There is little evidence regarding the practice and learning of cognitive tasks in the cold. However, memory registration has been shown to be progressively impaired with decreased core temperature from a level of about 36.7°C, while recall of previously learned data proved highly resistant to effects of lowered body temperature (58). Impaired memory registration may have hazardous consequences, eg, for divers memorizing a safe return route in cold water (58).

The significance of level of skill has been pointed out with regard to the effects of heat on vigilance performance (59, 60). There is evidence that skilled subjects are better able to maintain performance under thermal stress. In his analysis of the conflicting evidence with regard to vigilance performance, Hancock cited two studies in which no effects of heat on performance were found. He pointed out that in both these studies the task was such that highly practiced subjects, as used in these cases, could achieve a high degree of automation in their performance and thereby reduce sensitivity to the effects of environmental stress. However, a study by Wenzel & Ilmarinen (61), of one highly practiced subject exposed to heat, indicates that unimpaired performance may be achieved at the cost of greater effort, as measured by a superelevation in heart rate.

In regard to learning and practice it is interesting to note the work by Poulton & Freeman, who studied transfer effects in experimental studies (62). The authors cited several examples of experiments in which subjects exposed to an experimental stressor perform poorly and then continue to perform poorly in later tests under more optimal conditions. One interpretation may be the adoption of inadequate methods of work under stress, the inadequate methods then persisting even when the stress is relieved. Even if the practical significance of such possible effects cannot at present be assessed, they are certainly of note for the design of repeated measures experiments.

In view of the significant practical applications, it is clearly important that the effects of different practice and training models be clarified. A few tentative conclusions may be drawn from the evidence presented. The effects of practice conditions may differ at different stages in the skill acquisition process. Thus acquiring a certain level of skill under optimal conditions prior to an encounter with adverse conditions may be advantageous during the early stage of learning. This approach has been advocated in connection with other types of psychological stressors (63). Similarly, a high level of practice on some tasks of, eg, sustained attention may promote a performance strategy less amenable to negative influence. Experience of adverse conditions may, however, enable more suitable strategies to be developed at a later stage in the learning process.

Concluding remarks

The ultimate aim of applied research in this area is to reduce the negative effects and possible risks associated with work under thermal stress and to increase effectiveness. Broadly speaking, the thrust of such endeavors can be aimed in two directions, towards the environment and the situation or towards the individual. By improving clothing and protective equipment, redesigning the tasks to be performed and the tools with which to perform them, and using different technical solutions to minimize the impact of the environment, one can create conditions favoring improved performance. Some thermal stress situations will, however, still remain less amenable to the achievements in technology and protective equipment, due, eg, to the unpredictability of the weather and the elements, the conflicting thermal demands of people and the products and processes with which they are working, and economic factors.

A complementary approach is to regard the individual and to consider how the faculties of withstanding the impinging influence of environmental stress can be optimized in a specific situation. Further work on the significance of training and skill is required to clarify how this possibility may be accomplished.

In order to attain genuine improvement in performance under thermal stress, actions must be based on a theoretical understanding of the nature of the effects. Some advances in this direction seem to be under way in providing models which can account for the diverse effects observed. As always, there is a need for more data of a systematic nature. Detailed experimental planning and analysis of the data are also necessary to expose not only the possible increments or decrements in total performance, but also shifts in strategy, transfer effects, and interactions due to individual differences. In this connection noneffects are also of interest when the patterns are established, although it has been observed that such effects may be less likely to be reported (3).

Finally, in interpreting research results, one should perhaps recall that they are often achieved by selected groups of healthy young men who are highly motivated and subject to relatively brief periods of exposure. The everyday occupational situation may differ considerably. While this is hardly an original observation, nor exclusive to the domain of thermal stress, it may bear repeating.

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Thermoregulatory models

Recent research, current applications and future development

by Jürgen Werner, PhD¹

WERNER J. Thermoregulatory models: recent research, current applications and future development. *Scand J Work Environ Health* 1989;15(suppl 1):34—46. This review traces the efforts of different fields of thermoregulatory modeling. The aims of the three diverging branches can be characterized by (i) insight into functional physiological mechanisms and prediction of physiological phenomena, (ii) prediction of human performance for the protection of industrial workers or military personnel, and (iii) prediction of the impact of accidents, diseases, and clinical treatments. Common current and future efforts may be recognized which improve the physiological quality of the models for purposes either of physiological research itself or of promotion of the field of application, namely, (i) to approach the models to real geometry and anatomy of the human body, (ii) to simulate more adequately heat transport processes induced by the circulating blood, (iii) to implement more sophisticated regulatory concepts, (iv) to take into account interaction with other regulatory systems. "Environmental Ergonomics" should be an adequate forum for linking these diversified fields together.

Key terms: circulatory heat transport, geometry of the body, interaction of physiological systems, mathematical simulation, regulatory concepts, temperature regulation.

General development in thermoregulatory modeling

The flourishing early era for the physiological modeling of the human thermal system has been clearly outlined in the famous review by Hardy in 1972 (1), which turned out to be a kind of epilogue to modeling in fundamental thermal physiology itself during the following decade. Milestones of these earlier physiological developments have been the Stolwijk model (figure 1 A) (2, 6), which is still the basis of many other modifications and applications, mainly in areas other than physiology, and the Wissler model (figure 1 B) (3, 7), which has been refined and enlarged in a very efficient way and is still under further development (8). Whereas the pioneers of physiological modeling had to cope with the prejudiced opinions that simplification and inaccurate models were an inadequate tool in view of the exact and complex biological reality, the further development of refined models in physiology has been impeded by the argument that the results emerge with an arithmetic precision which is unjustified in light of the inaccuracies of physiological measurements and data. Nevertheless many new and stimulating developments have taken place in diverse areas during the last decade, and these developments are often characterized by the fact that neither the modelers nor the physiologists take any notice of each other. This situation is, of course, very dangerous and unfruitful and should

be corrected by a linking together of the efforts and results which already exist. Experimental research in thermal physiology is in full progress [see, eg, *Thermal Physiology* (9), *Heat Stress* (10), both edited by Hales] and should be given more attention and credit by some modelers. On the other hand, some physiologists still have to recognize simulation as a valuable complementary tool to experimental research. A possible basis for renewed common efforts was established by the Yale Debating Symposium on Thermal Physiology (11), which, in conclusion, confirmed the research value of thermoregulatory models.

The present report is intended to serve the purpose of combining experiences, results, and efforts in diverse areas by reviewing the development in physiology, mechanical and chemical engineering, ergonomics, biomedical engineering, medical physics, and clinical areas such as radiotherapy and the treatment of hypo- and hyperthermia. However, the whole spectrum is too broad for complete coverage of the literature. Therefore I have concentrated on a personal selection of contributions from many scientific fields during the last decade. The more or less detailed descriptions come from my own experience and do not reflect the grade of relevance of single contributions, nor does the omission of modeling contributions imply lack of significance.

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Recent and future developments in thermoregulatory modeling

Three diverging branches may be recognized from the last decade. They are characterized by three different

aims and purposes, namely, (i) insight into functional physiological mechanisms and the prediction of physiological phenomena, (ii) the prediction of human performance for the protection of industrial workers and military personnel, and (iii) the prediction of the impact of accidents, diseases, and clinical treatments.

Clearly, prediction is the common feature, but the main objectives in the first branch, ie, the physiological branch, are to understand the regulatory concepts and the interaction with other systems of the body, to extrapolate to variables not experimentally attainable, and to simulate unperformable experiments. The sec-

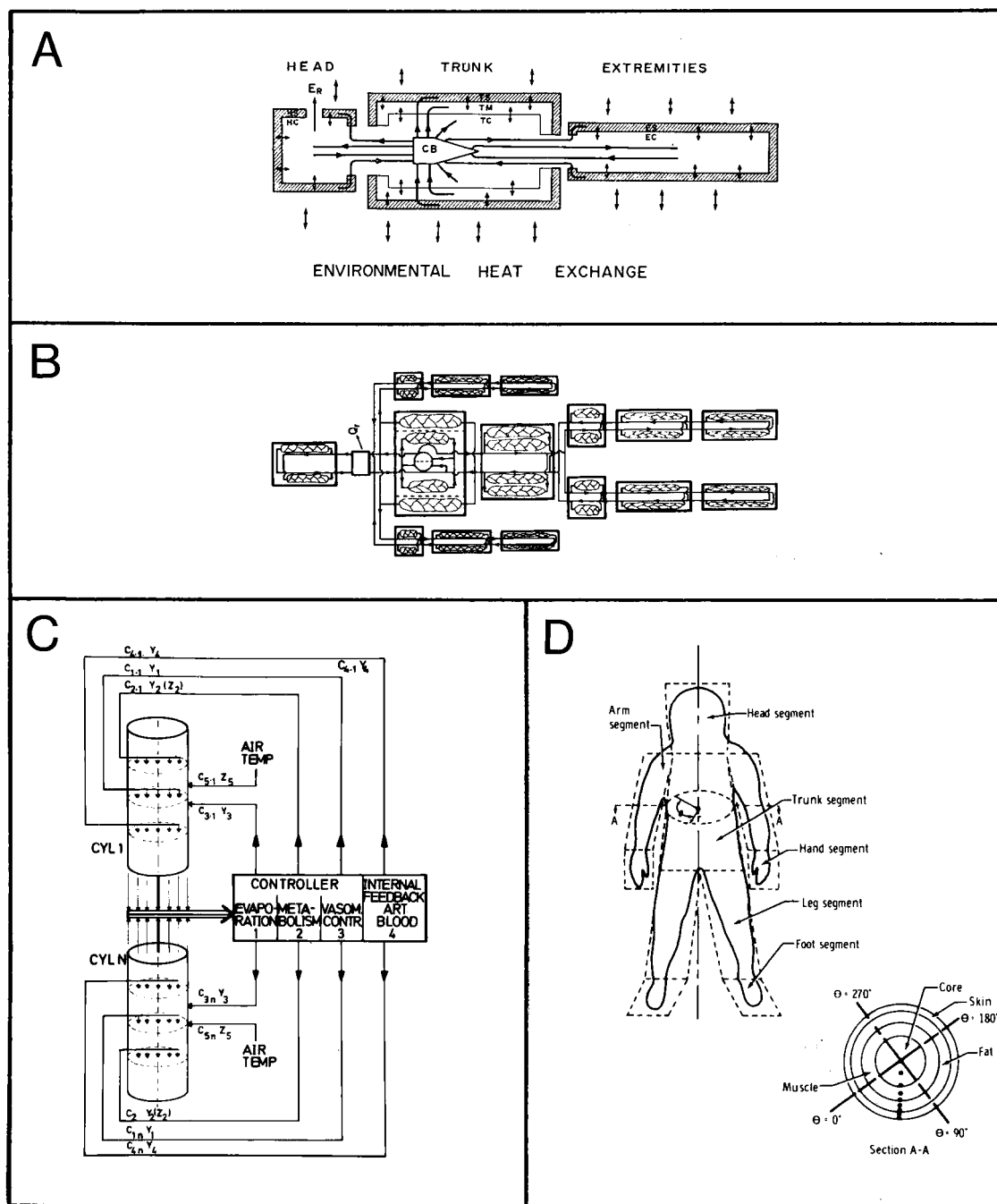


Figure 1. Examples of the classical versions of "cylindrical" thermal models. Part A shows the first version of the Stolwijk model (2) (reprinted with permission), a lumped parameter model, closed-loop; part B shows the second version of the Wissler model (3) (reprinted with permission), radial dependencies, open-loop; part C shows the first version of the Werner model (4), radial dependencies, closed-loop; and part D shows the first version of the Kuznetz model (5) (reprinted with permission), radial and angular dependencies, closed-loop. (CYL = cylinder, TEMP = temperature, VASOM = vasomotor, ART = arterial)

ond branch is producing models primarily to learn the limits of performance and to calculate the effects of harsh natural environments such as the desert, the arctic, the atmosphere, or the ocean. Special emphasis is placed on workers in technically evoked environments, eg, workers in mines, steel works and glass factories, air crew members, and astronauts. The objective is, on one hand, a higher utilization of manpower and, on the other, the prevention of diseases and accidents. The third branch is concerned with the consequences of diseases and accidents, because they either are currently inevitable or occur because of insufficient precautions. Important aspects are the treatment of accidental hypo- or hyperthermia and also diathermy and radiotherapy. Although these developments take place independently of one another, common current and future efforts may be recognized which improve the physiological quality of the models for purposes of either physiological research itself or promotion in the field of application, namely, (i) to make the models approach the real geometry and anatomy of the human body, (ii) to simulate more adequately the heat transport processes induced by circulating blood, (iii) to devise more sophisticated regulatory concepts, (iv) to take into account interaction with other regulatory systems, and (v) to account for individual differences.

Recent developments towards the real geometry and anatomy of the body

The complexity of existing models depends primarily on the purpose of the models. The early Stolwijk model (2) was confined to three cylindrical body compartments with two or three concentric layers plus a central blood compartment allowing one to assign the same number of different values to different parameters and to compute the temperatures of these elements plus the global effector responses. The model is a reduction of complex reality and has turned out to be very useful in various applications, especially in the prediction of performance in hot environments. It has been modified and adapted by the originator himself (6) and by many others. Montgomery (12) and recently Tikuisis et al (13) used a special version with additional temperatures in each element for calculations of the effect of cold immersion. Konz et al (14) improved many details and showed good experimental validation. Special reference was given to clothing in the adaptation of Smith & Twizell (15). A considerable increase in the number of elements was introduced by Gordon et al (16) with the effect of better validation with respect to responses to cold exposure. A recent version of the early Wissler model computes 225 temperatures in 15 elements plus many other variables. [See Wissler (8) and the following discussion.]

All these models, although very successfully used in special applications, fail to account for temperature distribution in any spatial direction other than radially outward from the body centerline.

In 1975 and 1977 I introduced the principle of spatially distributed parameters into thermoregulatory modeling (figure 1 C) (4, 17), but the version presented in 1975 was confined to the dynamics of radial temperature profiles. Kuznetz (5) developed a two-dimensional transient model (figure 1 D), which, however, like all its predecessors, adhered to the approximation of the human body by various cylindrical elements and to the simplification that the only thermal transfer between body compartments is via circulating blood. However, as analyzed by Buse & Werner (18), the geometry and inhomogeneity of the body is the most important feature if one aims at a computation of temperature profiles close to reality. Simulations are far more sensitive to alterations of these features than to changes of other physical or physiological parameters.

In 1977 a data base of the macroscopic anatomy of the human body was developed by photogrammetric treatment of three-dimensional anatomic models (Somso Company, types: AS 23, NS 9—15) and the further analysis of the thereby obtained sectional maps; the procedure has been described in detail by Kelterbaum et al (19).

The global data of the available anatomic model are height 1.76 m, weight 67 kg, mean density $107 \text{ kg} \cdot \text{dm}^{-3}$, surface 1.8 m^2 , and volume 62.7 dm^3 . For computer treatment the anatomic model was projected on a three-dimensional grid, for which 0.55 cm was chosen for the head and the extremities and 1.1 cm was chosen for the trunk.

This procedure makes possible a representation of vessels with a diameter of ≥ 1.1 and ≥ 0.55 cm and of all essential organs of heat production. With the additional aid of anatomic atlases and data on the distribution and density of tissue a satisfactory digital representation of the body has been obtained. A higher resolution would have been desirable at many sites, eg, in the hands and feet or in other parts of the body for a more precise modeling of the circulatory system. Although computer tomography would make possible such a data base now, such a simulation would go beyond the capacity of currently available computers. Figure 2 shows examples of the head, leg, and trunk sections from the digital atlas. Different symbols represent different body components, which in this treatment of the body add up to 54 different types. The structures to which different values of parameters may be attributed are 16 skin areas, 10 muscle areas, 6 types of vessels, 4 areas of the central nervous system, the heart, the liver, the lungs, the kidney, the stomach, the gut, the fat, the connective tissue, the bladder, the thyroid gland, the spleen, the esophagus, the trachea, the eyes, the skeleton, the skull, air, and blood. The parameters attributed to these 54 types of body components are heat conductivity, specific heat capacity, density, basal specific metabolic heat production, and specific blood flow.

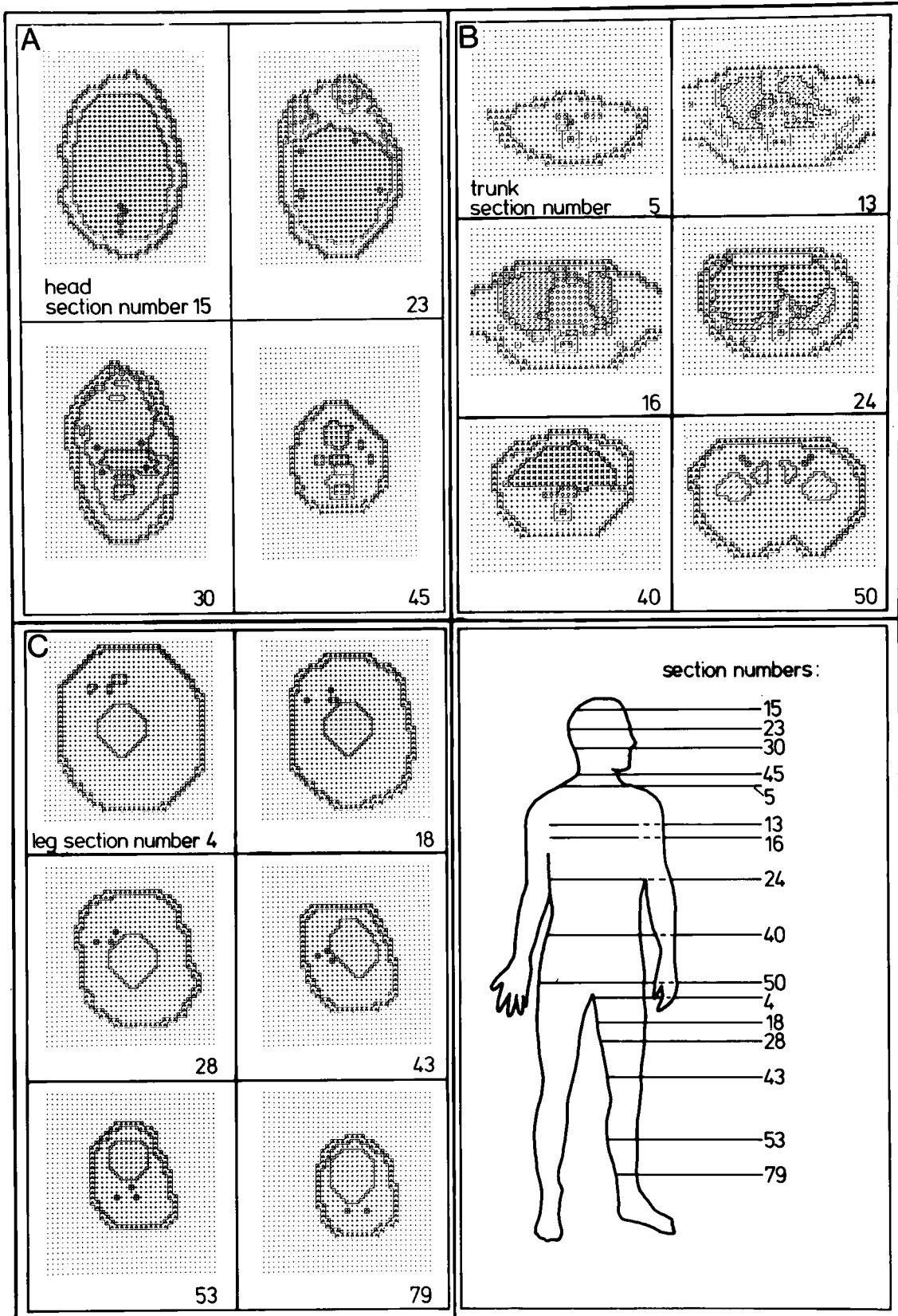


Figure 2. Examples of transverse sections from the digital atlas for the three-dimensional (noncylinder) model of Werner & Buse (20).

The passive system is essentially described by a three-dimensional diffusion equation with coefficients as functions of the local coordinates x , y , z . Such equations are usually solved by the finite difference methods, and especially by a modification of the alternating direction implicit method. For the following two reasons this method seems to be advantageous: (i) it is an implicit method, the difference equation involved being stable for all quantities of Δx , Δy , Δz , Δt , and (ii) by partitioning one equation with three implicit directions into three equations with one implicit direction each, an algebraic reformulation results in three tridiagonal systems which can easily be solved by Gaussian algorithm.

The simulation first delivered a realistic picture of the topography of temperatures under neutral conditions (20, 21). The compatibility of reality and simu-

lation was tested by experiments and through a comparison with values given in the literature. It was achieved solely on the basis of physical considerations and physiological data. An adjustment of parameters of the passive system is not necessary, and the computation should be equally suited to delivering temperature profiles which cannot be obtained experimentally.

The first temperature profiles of transverse sections of the body in the indifferent status ($T_a = 30^\circ\text{C}$) have been computed (figure 3). For the head, temperature is extremely constant. A decrease in skin temperature starts only at the skull. This phenomenon is due to the high metabolic and blood flow rate of the brain. The profiles of the extremities are, due to the lower metabolic and blood flow rate, more convex, but equally rather homogeneous and smooth. For the trunk, es-

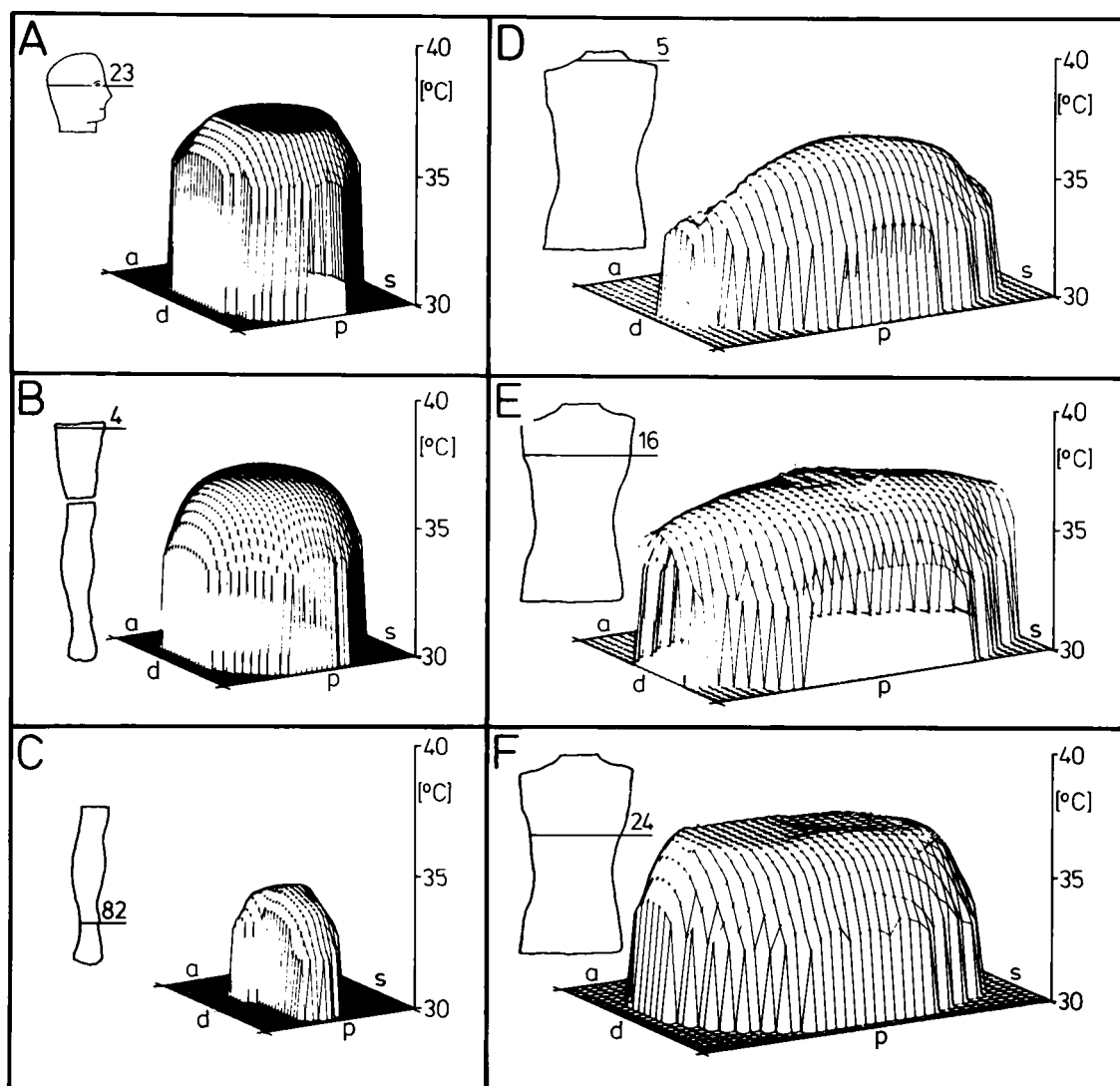


Figure 3. Temperature profiles of transverse sections in a neutral environment computed by the three-dimensional model (p = posterior, a = anterior, d = right, s = left. The sections are seen from caudal to cranial sites (see insets).

pecially the transverse profiles depend on the longitudinal coordinate. With the availability of more computer core capacity, it has become possible to compute the dynamics of every temperature profile within the body. For an example see figure 4.

A new two-dimensional version of the Wissler model will certainly fill a gap between the one-dimensional models and the three-dimensional model, which for many applications may be too complex.

Other approaches are primarily concerned with modeling the true anatomy of organs or parts of the body. An interesting new model presenting isotherms of the human thigh is under development (8). It uses an elliptical coordinate system and will, when provided with a finer grid near the surface, allow a more representative description of the subcutaneous fat distribution.

The thermal response of human thigh exposed to diathermy treatments has been described by Emery & Sekins (22), using the method of finite elements with a densely constructed grid in the vicinity of the diathermically heated zone and a relatively sparse grid elsewhere with the exception of the surface. The simulation can be used to predict the response of living tissue to a variety of treatment protocols, and it is particularly used for the definition of the correct diathermy dose for tumor treatment. A comparison of experimental and numerically determined transient responses shows good agreement, particularly in the region of the heated muscle.

The method of finite elements has also been used by Iskander & Khosdel-Milani (23) for calculating temperature distributions in cross-sections of the human thorax, also with respect to hyperthermia treatments. Whereas these are two-dimensional treatments, Olsen et al (24) presented a finite element representation of the monkey head by rotating one section about the heavy base line. This procedure is, of course, completely inappropriate for the lower head, but it seems to be acceptable for the brain. It was used to predict the effects of arterial blood cooling by cardiopulmonary bypass.

The effects of inhomogeneities and finite boundaries on temperature distributions with respect to application to tumors were analyzed by Jain (25) by modeling three spherical zones, ie, a heating core of a probe, the periphery of the probe, and a perfused medium. This contribution is interesting both with respect to radiotherapy and to thermal physiology because the model of a perfused porous medium has been used to circumvent a mathematical description of the complexities of the microcirculation of a tissue. (See the following discussion.)

A detailed discussion of the mathematical modeling of heat transfer with respect to cancer therapy has also been given by Jain (26), and a special survey of the simulation of hyperthermia in tumor treatments has been written by Strohbehn & Roemer (27). A two-dimensional, axi-symmetric, inhomogeneous patient

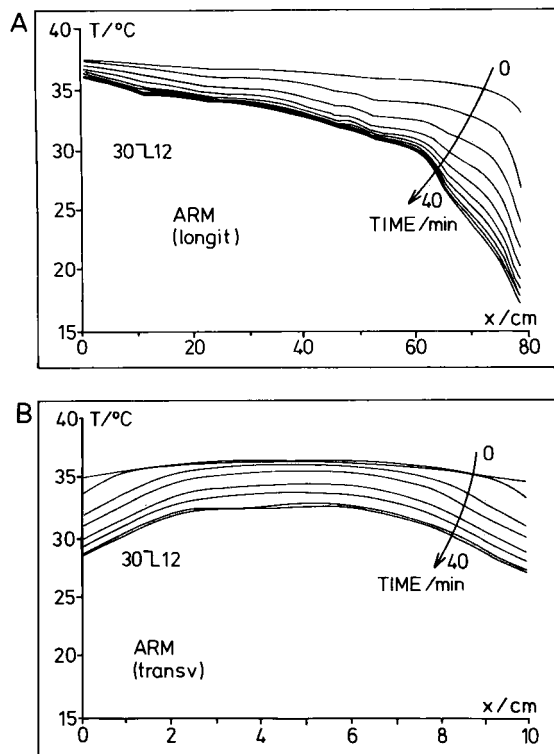


Figure 4. Example of the dynamics of the central longitudinal (longit) (A) and radial (transverse, transv) (B) temperature profiles of the human arm in response to a stepwise change of air temperature from 30 to 12 $^\circ\text{C}$ (humidity 30 % and air speed 0.1 $\text{m} \cdot \text{s}^{-1}$).

model has been used by Paulsen et al (28) for computing temperature profiles for concentric coil induction heating devices. The finite element grid and an example of isotherms are shown in figure 5.

Another contribution should be mentioned in this context, although it uses a lumped parameter model (65 elements), because it is designed to evaluate the effects of thermal compensation (evaporative spray cooling) in hyperthermia treatments (29). However, it needs further experimental validation.

Recent developments towards a better representation of circulatory heat transfer

Convective heat transfer plays an essential role in temperature regulation. It is determined by the vessel geometry and the flow conditions within the vessels. The parameters of heat transport are the heat transfer coefficient vessel/tissue, viscosity, density, the heat capacity of blood and flow velocity, diameter, and the length of the vessel.

Whereas the aforementioned models assumed that the thermally significant heat transfer takes place in the capillaries, it was shown by Chen & Holmes (30) that thermal equilibrium is already reached in vessels of medium diameter. This phenomenon has been con-

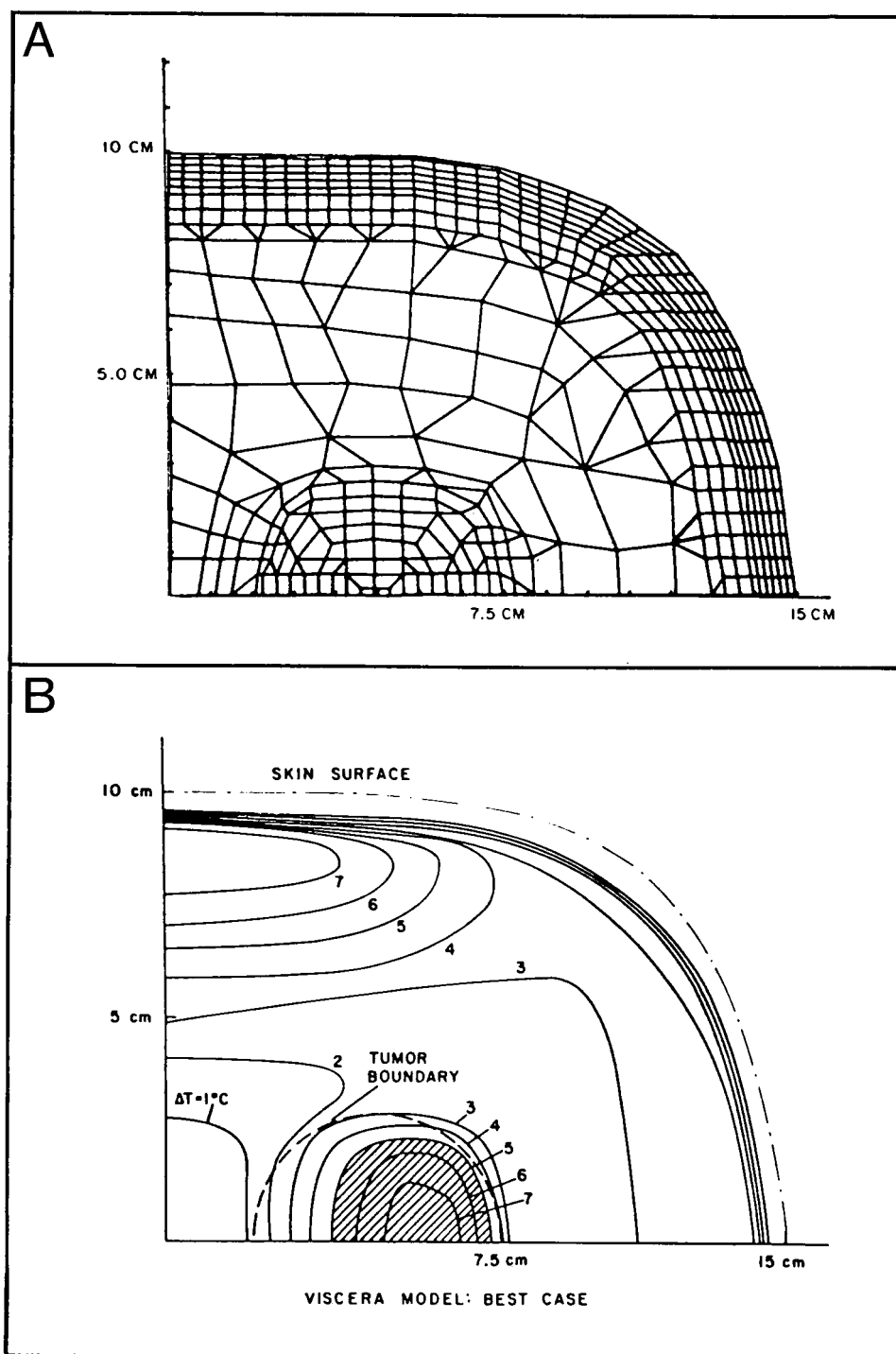


Figure 5. Example of modeling hyperthermia treatments (from Paulsen et al (28) and Strohbehn & Roemer (27), with permission). [A = the finite element grid used for calculating the isotherms for concentric coil heating; B = example of isotherms for concentric coil heating (viscera model: skin held at 20°C , blood flow in tumor = 0, in viscera $27 \text{ ml} \cdot 100 \text{ g}^{-1} \cdot \text{min}^{-1}$, in muscle/fat $18 \text{ ml} \cdot 100 \text{ g}^{-1} \cdot \text{min}^{-1}$)].

firmed both by further theoretical (31) and experimental studies (32). The lower limit for thermal nonequilibrium seems to be 50 to 100 μm for the arteries

and 400 μm for the veins. In this respect smaller vessels are thermally insignificant. These findings contrast with the view of former modelers that most heat trans-

fer occurs in the capillaries, and it suggests that vascular heat transfer analysis must take into account the vascular architecture of the 50- to 1000- μm vessels in which most heat transfer occurs. Therefore a three-layer representation of heat transfer in surface tissue has been developed both by anatomical and by theoretical investigations (31, 33). It takes into account the variation of the number, density, size, and flow velocity of the countercurrent arteriovenous vessels as a function of depth from the skin surface, the directionality of blood perfusion in the intermediate layer with transverse vessels, and the superficial shunting of blood to the cutaneous layer. The simplified three-layer model with the deep, intermediate, and cutaneous layer is shown in figure 6.

The body is thus able to conserve heat in a cold environment by providing a much thicker outer conduction layer than had previously been realized (34). On the other hand, the close proximity of these thermally insignificant vessels to the surface provides for a significant augmentation of the heat loss through the skin, and this augmentation is primarily controlled by cutaneous circulation. In general, the intermediate layer dissipates the small temperature perturbations due to the thermally significant vessels in both the deep tissue and the cutaneous layers. The circulation in the cutaneous layer is independent of the skeletal muscle circulation. It is provided by a few larger vessels which rise obliquely from the large arteries and veins, penetrate the skeletal muscle, and then connect directly with the larger vessels of the cutaneous plexus. The relatively large, thermally significant superficial vessels lie in the lower portion of the cutaneous layer. The critical pathways in the blood flow regulation of the cutaneous layer are the 20- to 40- μm arteriovenous anastomoses. While the vertical connecting vessels are themselves too small to transfer much heat into the more superficial regions of the skin layer, their vasodilation and vasoconstriction significantly controls the flow of blood into the more superficial plexus.

For a 5 to 10°C difference between the local arterial temperature in the major supply vessels and the skin temperature, a countercurrent arteriovenous temperature difference of only 0.1 to 0.2°C was found in the deep layer. The distribution of capillary perfusion does have a significant effect on this small arteriovenous temperature difference. Jiji et al (33) concluded that the principal mechanism by which the tissue and the microvasculature exchange energy is the slightly incomplete countercurrent exchange that occurs in the thermally significant vessels.

On the basis of these findings, Weinbaum & Jiji (35) developed a new simplified bioheat equation for the effect of blood flow on local average tissue temperature. The new theory claims that the vascularization of tissue causes it to behave as an anisotropic heat transfer medium. The Weinbaum-Jiji impact on the bioheat equation has recently evoked a continuing debate. Wissler (36, 37) has pointed out that the Wein-

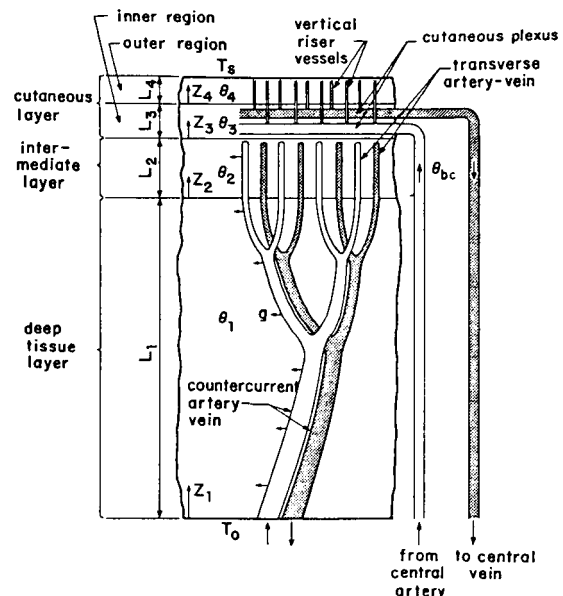


Figure 6. Simplified three-layer model showing basic vascular structure in deep, intermediate, and cutaneous layers (from Song et al (34), reprinted with permission). Only thermally significant counterpart vessels are shown in regions L_1 and L_2 . The capillary beds have been omitted throughout.

baum-Jiji formulation is probably appropriate for vessels that are smaller than 200 μm in diameter, but that its applicability is questionable for larger vessels, where blood flow is nearly perpendicular to the temperature gradient and where there is little enhancement of those elements of the thermal conductivity tensor that affect the radial temperature profile. It has been suggested that the bioheat equation should include elements of both the Weinbaum-Jiji formulations and the classic formulations treating the convective effects of the moving blood as a volumetric isotropic heat source and the assumption that the heat transfer is proportional to the blood flow rate and the temperature difference of blood and adjacent tissue.

Recent developments towards modeling the regulatory concept

Most of the published equations for the control of the thermoregulatory effector mechanisms are based on the concept that there are two integrated drives, one central signal and one peripheral signal. [For a review see Simon et al (38) and Werner (39).] Both additive and multiplicative processing of the two signals has been proposed. A comparison of the results of these models shows that, in spite of the apparent divergence, all the values are within the inter- and intraindividual variations measured by various authors. In view of this span of experimental data, it does not seem to be justified to favor a nonlinear approach. Moreover for moderate thermal load all models deliver comparable results as to the three global variables effector activi-

ty, core temperature, and mean skin temperature. There is general agreement that the weight of the peripheral signal has to be assessed at between 10 and 20 %.

With the use of more elaborate models of the passive thermal system, the question has to be asked of whether such simple controller concepts are able to account for the distributed temperature field in the cold. Especially the question of whether the inhomogeneous temperature field is primarily due to the inhomogeneous structure of the body or, in addition, to a distributed controller concept, ie, one must examine whether the spatial pattern of effector distribution is maintained after thermal load or whether there is active modification and control. In a comparison of both possibilities the generally used weighting of the thermal input signal was only slightly modified according to the results of Heising & Werner (40) and also other results which required that muscle temperature, at least, should be taken into account, the weighting of which should be near that of the skin temperature signal (10 % being assigned to both and 80 % to the core; the signal threshold being assumed to be 37°C). The increase in metabolic heat production is obtained by multiplication of the weighted thermal input signal by the controller gain. With the use of the three-dimensional model of the passive system that has al-

ready been described (20, 41), the optimal lumped parameter gain that delivers the best agreement with the global experimental variables was determined to be about $5000 \text{ W} \cdot \text{m}^{-3} \cdot ^\circ\text{C}^{-1}$, a value in agreement with that of other reports. However, when the spatial distribution pattern of temperature in the cold is examined, it becomes clear that maintaining the pattern of distribution of heat production yields amounts that are too high for the arms and legs, which do not contribute much to the stabilization of central trunk and head temperatures. This phenomenon is illustrated by figure 7. In this figure the simplest distributed parameter approach delivering a correct temperature distribution is given in the parts labeled B; they take into account at least three different regions, the gain factor varying from 5200 to $0 \text{ W} \cdot \text{m}^{-3} \cdot ^\circ\text{C}^{-1}$. There is therefore a concentration of heat production in the central areas and simultaneously a reduction of dry heat loss. In conclusion, for cold defense, a spatially distributed control of heat production is required.

A similar, but minor, relevance of the distributed control concept has been confirmed with regard to blood flow rate. However, the influence of the values of distributed minimal rates is more relevant than locally differing gains. On the other hand, the influence of distributed controller structures is not so obvious in the defense against heat with regard to evaporative

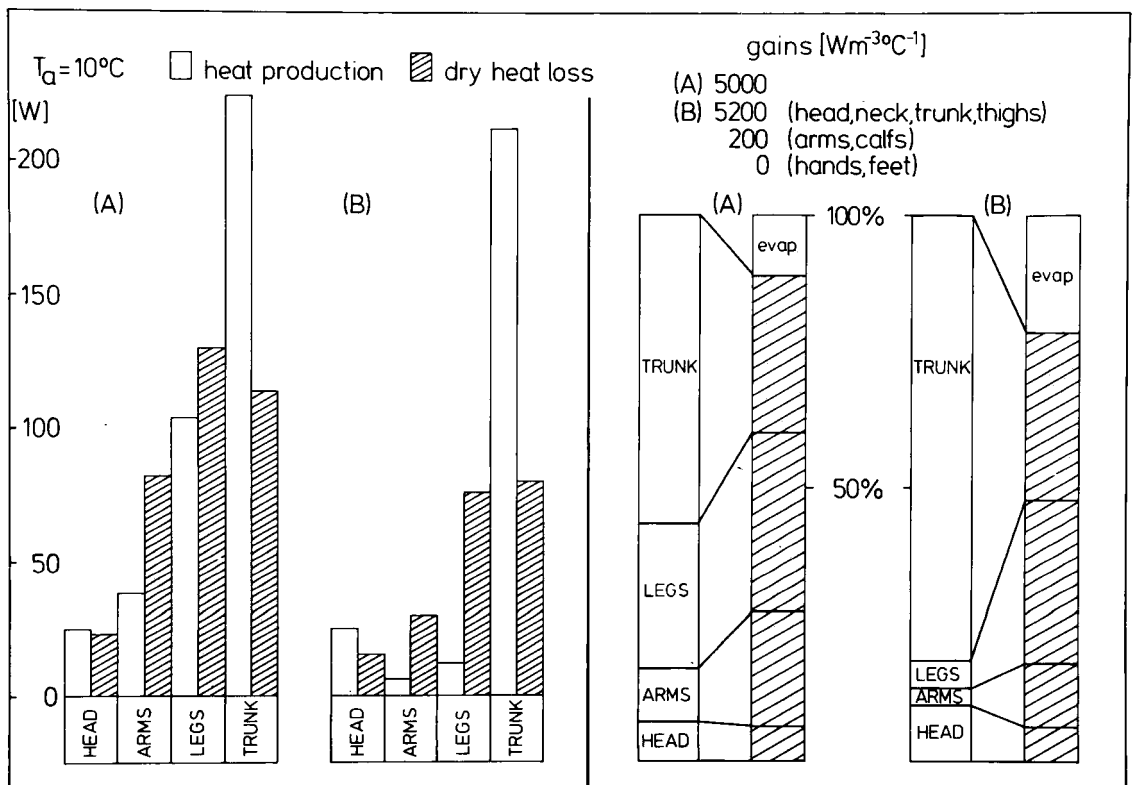


Figure 7. Distribution of heat loss and heat production according to the best case of lumped parameter control of skeletal muscles (A) and according to the simplest distributed parameter control (B) compatible with experimental results. Air temperature 10°C . Three dimensional model of Werner & Buse (20) used for the passive system.

heat loss. There are only very small temperature differences in the body after a stronger heat load. Therefore, for sweating rate, the question of whether there is distributed control or not can only be tested with the use of different thermal loads to different parts of the body.

Developments towards modeling interaction with other regulatory systems

Thermoregulation is highly interconnected with other regulatory systems of the body. There is a strong interaction with metabolism, circulation, respiration, osmoregulation, and other systems. Most of the models reduce their couplings to the minimum extent necessary to simulate thermal performance. However, with further insight into the physiological mechanisms, it becomes more and more necessary to take into account the multilateral influences and, in special situations, the competition between these subsystems. Although there is no model which can be called complete in this respect, the recent Wissler model (42) presents many interesting features. It contains mass balances for oxygen, carbon dioxide, and lactic acid in order to provide information required in the control equation for perfusion and ventilation. As for metabolism, the equations used in the model are based on a greatly simplified metabolic scheme, which does, nevertheless, include most of the essential features. It is assumed that energy is obtained from the oxidation of carbohydrate, which can be represented by glucose. The objective of the metabolic reactions involved in exercise is to form adenosine triphosphate from adenosine diphosphate and orthophosphate. Adenosine triphosphate is readily hydrolyzed in muscle cells and ultimately provides the energy needed to do mechanical work. The chemical reactions are incorporated into the model through material balances for each chemical species in tissue and blood. As for oxygen, it is assumed that equilibrium exists between oxygen in myoglobin and oxygen in hemoglobin. For carbon dioxide, equilibrium is assumed between the carbon dioxide stored in tissue and blood with a tissue concentration 50 % of that in blood. Lactate is supposed to be transferred from muscle to blood at a finite rate proportional to the difference in concentration. For the lungs, a special term is required to account for the exchange of gas between pulmonary capillaries and the alveolar space.

In evaluations of the exchange rate through the lungs, the periodic character of pulmonary ventilation is neglected. The model works with time-averaged values of such quantities as the ventilation rate and the temperature, humidity, and the partial pressure of oxygen and carbon dioxide in expired gas. The lungs are heated as a well-mixed region of constant volume through which gas passes at a constant rate.

Although this model still operates with an arterial and a venous pool, it contains some special circulatory features that take into account the fact, eg, that one

vein from each leg flows into the abdominal section of the trunk and that in the thoracic section all venous streams terminate and arterial streams originate. It is assumed that the temperature of the blood entering the pulmonary capillaries is equal to the mixing mean temperature of the venous streams entering the right ventricle.

The control equations are, on the whole, rather sophisticated. Wissler emphasizes that inferences concerning physiological mechanisms should not be drawn from the equations because they have been specifically designed to result in a system which responds to thermal stress and exercise in a manner similar to human subjects. This recommendation holds especially for the perfusion equations, which are elaborated well in the model but for which very few solid physiological data are available. The shivering equations, too, are given very detailed treatment consistent with various physiological findings. Because of the enormous amount of variability in experimental data, sweating is represented by a comparatively simple linear relationship. At present, this model is the most complete with respect to the interaction of systems. It is well validated in various applications, such as for exercise at increasing rates, head-out immersion in water, exposure to hyperbaric mixtures of helium and oxygen, and head-out immersion of lightly clothed subjects in cold water while resting and swimming, also followed by rapid rewarming in warm water. The model is, of course, still being developed. It will be worthwhile to extend it to a two-dimensional form.

The interaction or competition of systems is still a rare subject in modeling. Leigh (43) combined a special version of the thermoregulatory Stolwijk model with the Grodins model (44) of respiratory control. As respiratory heat loss can be important for miners, mine rescue workers, firemen, astronauts, and others, the model has potential practical value in addition to its role in the study of physiological control mechanisms.

Individual differences

For various applications it has been pointed out that there is need for taking into account individual variations. Some models principally allow for subject weight and body fat, especially mean skinfold thickness. However, most cold studies continue to be performed without determining subcutaneous fat thickness, and this lack could explain many variations between individual responses (8, 45). Although many models are very useful in the description of mean behavior, thermal and work performance, tolerance limits, etc, should also be predicted for the individual. This recommendation implies, however, that at present the most complex models are not suited for such tasks. In general, physiological models are still difficult to handle for individual evaluation, and such evaluation is still the domain of the practically useful empirical models such as that developed by Givoni & Goldman (46) and others.

Concluding remarks

The spectrum of current activity in thermoregulatory modeling is broader than it seems at first sight. However, the center of activities has shifted from physiological laboratories to diverse applied sciences. This is a positive development on one hand because most of the recent models are designed for definite applied purposes and demonstrate their usefulness by delivering practicable results. On the other hand, this is a dangerous development because modelers get used to working without contact with physiology, and this situation gradually leads to more phenomenological or heuristic models and to less functionally physiological models. In the long run this trend diminishes the amount of confidence in predictive results because validation is, if at all, primarily inferred from the compatibility of the system performance in simulation and in reality for certain selected situations and not necessarily from the congruence of the physical laws and mathematical operations used in simulation and reality. Furthermore, the impact of modeling on the design and the results of physiological experimental research is reduced to a minimum if the applied sciences and physiology operate independently of one another.

What are the main factors still impeding a more rapid progress in thermoregulatory modeling? Computer capacity, which formerly restricted thermoregulatory simulation to rather simple models, is principally no longer a factor. The spectrum of models now available covers all grades of complexity and all levels of computer types from the cheapest personal computer up to supercomputers, including array and vector processors. The main factor is still the lack of physiological knowledge about the structure and functional mechanisms of subsystems and their interaction within the organism. This situation is primarily due to the immense complexity of the real system. It is a hierarchical multilevel system, meaning, eg, that operating changes generated in higher centers may occur on the basic system level as spontaneous changes or as long-term adaptive changes. Furthermore, thermoregulation is part of an interacting multigoal system imbedded in various control loops of the body which influence one another or may even compete with one another. Thus experimental analysis has to cope with the enormous difficulties of isolating subsystems and analyzing their interactions. Moreover thermoregulation is a distributed parameter system, meaning that all variables and parameters are spatially distributed within the body, ie, are functions of time and the three-dimensional local coordinate. This phenomenon explains the difficulty of analyzing representative elements, variables, and parameter values. As for the active (controlling) subsystems, there is practically no adequate experimental method of analyzing afferent and efferent information processing. Evoked potentials are as inadequate as single unit recordings, not to mention the problems evoked by anesthesia.

Besides the lack of insight into functional mechanisms, the second factor is the lack of definite basic parameter values, which in the life sciences are not compiled in a systematic way, as is done in physics or the engineering sciences. Many studies are restricted to the principle effects. Routine quantitative parameter screening is not popular and probably not accepted by physiological journals. Generally there is no awareness that the determination of complete sets of data will be appreciated by all colleagues involved in biomedical simulation. On the other hand, it cannot be overlooked that, for some classes of parameters, there is no experimental approach or no measuring technique available. Finally intra- and interindividual differences impede the edition of complete parameter tables. [The pure compilation of the outer dimensions of the body comprises a three-volume data book (47)].

Third, there is apparently a lack of possibilities for validation. In addition to the obvious impossibility of testing all results experimentally, it is a fact that experimental research programs especially designed for validation are generally not supported, as they comprise types of experiments which were done formerly "in principle."

The question now arises of what can be and should be done besides waiting for further developments and new results in basic physiology. It is the interdisciplinary cooperation in biomedical modeling which has undergone much frustration during the past several decades and in many areas has degenerated to a pure declamation, but which has to be revived for the sake of more fruitful progress. More integrative research has to be encouraged and supported. Narrow-minded defense of special areas against invaders must be condemned. The multidisciplinary approach of carrying out comparable research with different methods independently of one another has to be transformed into a real interdisciplinary approach of experts with overlapping knowledge and experience. It is no use defining more thoroughly the borders of physiology, applied physiology, clinical physiology, occupational physiology, ergonomics, and bioengineering. On the contrary, it is necessary to recognize, and to convince those who would benefit, that these areas necessarily comprise various common sets, which can only be attacked by the community of the sciences involved. "Environmental ergonomics," if understood as the integrative and coordinated efforts of human physiology and human engineering to analyze performance in harsh environments and to protect those who are submitted to it, should be an adequate platform to improve the fruitful development of both the experimental and the modeling approach.

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Modification of Vernon's globe thermometer and its calibration in terms of physiological strain

by Hans G Wenzel, MD, Alfons Forsthoff, PhD¹

WENZEL HG, FORSTHOFF A. Modification of Vernon's globe thermometer and its calibration in terms of physiological strain. *Scand J Work Environ Health* 1989;15(suppl 1):47-51. Six men wearing shorts performed treadmill work in about 150 climatic chamber experiments at several temperatures of Vernon's globe thermometer (t_{g}) from 25 to 50°C. Each t_{g} was produced partly by an equal air temperature (t_a) and a mean radiant temperature (MRT), partly by a lowered t_a (minimum 5°C) and an MRT elevated up to about 80°C above the t_a . With an increasing MRT and lowered t_a , respectively, body temperature, heart rates, and sweat losses decreased significantly. In another 55 experiments physiologically equivalent combinations of t_a and MRT were derived. According to the results a modified globe thermometer was built. It reduced the errors of Vernon's instrument by about 75 %. The remaining error of 25 % was due to changes in air velocity between 0.5 and 2 m · s⁻¹. The applicability of simple instruments like globe thermometers is obviously limited for the description of physiologically equivalent conditions of unequal t_a and MRT at various air velocities.

Key terms: globe thermometer, physiological equivalence, unequal air and radiant temperatures.

It is well known that radiant temperature may exceed air temperature considerably at many, particularly industrial, workplaces or in the open air and that effects of elevated radiant temperature on man may be compensated by lowered air temperatures within certain limits. In the evaluations of such climates, the globe thermometer of Vernon (1) has been used for many decades under the assumption that those conditions of unequal air and radiant temperature resulting in equal globe temperatures are also physiologically equivalent. However, it is not known if this assumption is correct, particularly in cases of large differences between air and radiant temperatures of, eg, 50 K and more.

There is good reason to conclude that the lack of knowledge about the accuracy of Vernon's globe thermometer is due to the fact that the experimental simulation of the needed climatic conditions requires a technically complicated and expensive climatic chamber. At the end of the 1970s, such a test room was constructed in the Institute of Occupational Health at the University of Dortmund. The chamber is similar to one developed and described earlier (2, 3). Figure 1 shows a horizontal section of the climatic chamber. A test subject sitting or working in the middle of the chamber can be exposed simultaneously to an air stream with temperatures down to the freezing point and to mean radiant temperatures of up to about 140°C. The oblong line, plotted in polar coordinates, in figure 1

demonstrates the distribution of radiation energy, produced in four so-called "radiation towers." In order to help clarify the aforementioned question of whether the physiological effects of unequal air and radiant temperatures are equivalent to those experienced at the resulting equal globe temperatures, four series of more than 400 climatic chamber experiments were carried out. Series 1 revealed inaccuracies in the globe thermometer of Vernon (1), series 2 concerned possibilities of improving Vernon's thermometer, series 3 was used for developing a modified globe thermometer, and series 4 dealt with advantages of the new globe thermometer and its calibration in terms of physiological strain.

Series 1

In about 150 experiments, six healthy young men wearing shorts and footwear were exposed to conditions

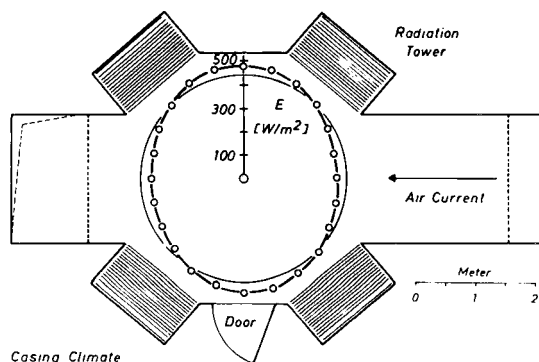


Figure 1. Horizontal section of the climatic chamber.

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of globe temperatures between 25 and 50°C (4, 5). The equal radiant and air temperatures were described by the unbroken diagonal line as shown in figure 2. They will be referred to in the text as “reference tempera-

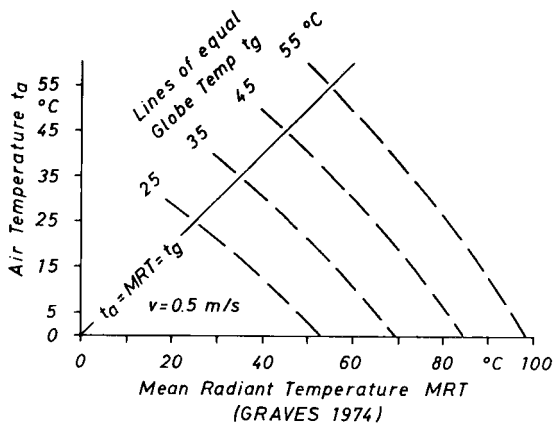


Figure 2. Lines of equal temperatures of Vernon's globe thermometer (t_g) (broken lines) at different air temperatures (t_a) and mean radiant temperatures (MRT) according to Graves (6). (Temp = temperature, v = air velocity)

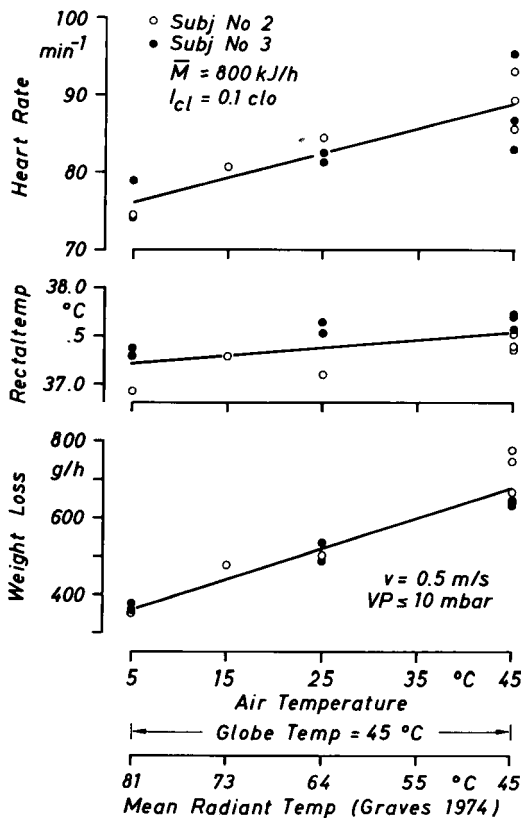


Figure 3. Some physiological responses of two subjects after 3 h of treadmill work in unequal air and radiant temperatures at a constant globe temperature of 45°C. ($\dot{M}$ = mean metabolic rate, I_{cl} = thermal insulation of clothing, v = air velocity, VP = vapor pressure, Temp = temperature)

tures.” The figure also shows the combinations of various air temperatures and mean radiant temperatures which result in equal temperatures of Vernon's globe thermometer according to previous investigations of Graves (6). The respective calculation according to older data of Bedford & Warner (7) results in slightly different curves.

Each desired globe temperature was produced first by an equal air and radiant temperature; in further experiments the mean radiant temperature was increased stepwise in combination with a stepwise reduction in air temperature. In each experiment, the subjects walked 4 km/h on a horizontal treadmill for 3 h in most cases. They were supplied with drinking water ad libitum.

Figure 3 demonstrates the results of 13 experiments carried out on two subjects working in air with a low humidity level, the air velocity being 0.5 m/s. In all the experiments, the globe temperature was kept constant at 45°C. If Vernon's globe thermometer were able to describe physiologically equivalent conditions correctly independent of the combination of air and radiant temperature, equal physiological reactions would be expected when the radiant temperature was elevated and the air temperature reduced respectively. According to figure 3 this result, however, was not obtained. By the end of the third hour the heart rate and rectal temperature had decreased significantly with an increasing radiant temperature and correspondingly a decreasing air temperature. The same applied to body weight (sweat) loss.

Similar experiments were carried out on the other test subjects, partly at other globe temperatures between 25 and 50°C and partly at an air velocity of 2 m/s instead of 0.5 m/s. Some additional experiments were also performed in which radiation from the front or back of the subjects replaced circular radiation. Without exception, unequal combinations of both the ambient temperatures that produced a constant globe temperature resulted in systematically different physiological responses. Sweat loss, for instance, decreased by about 300 g/h under the extreme conditions, corresponding to 50 % of the sweat loss at the reference temperature. Heart rate decreased up to about 30 beats/min. In other words Vernon's globe thermometer considerably underestimated the physiological effects of decreasing air temperature and overestimated the corresponding effects of increasing radiant temperature.

Series 2

In an attempt to determine the combinations of air and radiant temperature equivalent to actual conditions, 55 experiments were carried out with three of the six subjects included in series 1. The slanting line of the example in figure 4 confirms again the findings obtained earlier with a constant globe temperature. In additional experiments, the globe temperature was not

kept constant, but was instead elevated stepwise until the same physiological reactions were reached as had been obtained at the reference temperature. (See the horizontal line in figure 4.) At an air temperature of 15°C, for instance, the globe temperature had to be elevated by 10°C, from 45 to 55°C, to cause the weight loss observed at the reference temperature of 45°C. The results of all the experiments of this series have been summarized in figure 5.

Series 3

As has already been mentioned, Vernon's globe thermometer and the human body show different relationships between heat exchange with the environment by convection and radiation. The aim of the experiments of series 3 was to modify the original globe thermometer so that its heat transfer properties simulated those of the human body. More than 20 modifications were tested (8). Special emphasis was attached to technically simple changes acceptable to the practitioner making use of the instrument in daily life.

One successful modification was to change the diameter of the black globes used. A smaller diameter (diameter of Vernon's globe 150 mm) resulted in a higher heat transfer coefficient for convection. A globe with a diameter of 58 mm reached equal temperatures under the climatic conditions described as being physiologically equivalent at the low air speed of 0.5 m/s (figure 5). A slightly larger globe, 73 mm in diameter, proved to be suitable at an air speed of 2 m/s. This difference corresponds to thermodynamic experiences of physics. In order to save the practitioner the trouble of using different globes at different air velocities, a compromise was made. A globe with a 65-mm diameter, ideal for an air velocity of about 1 m/s, was built. Certain inaccuracies were likely for air velocities of 0.5 and 2 m/s, but they could be expected to be fairly small.

Series 4

To determine whether or not the conclusions drawn on the basis of the experiments in series 3 were valid, additional experiments were carried out which were similar to those performed in series 1. Three young men worked first at reference temperatures and then at stepwise reduced air temperatures and correspondingly elevated radiant temperatures, but partly at a constant temperature of Vernon's globe thermometer (t_{gv}) and partly at a constant temperature of the modified instrument (t_{g65}). Figure 6 shows the final values of the heart rates of two of the three subjects when an air velocity of 0.5 m/s was used. As expected from the results of the experiments in series 1, the heart rates measured under the t_{gv} conditions decreased with lower air temperatures. Under the t_{g65} conditions the heart rate of one subject (subject 9) decreased slightly

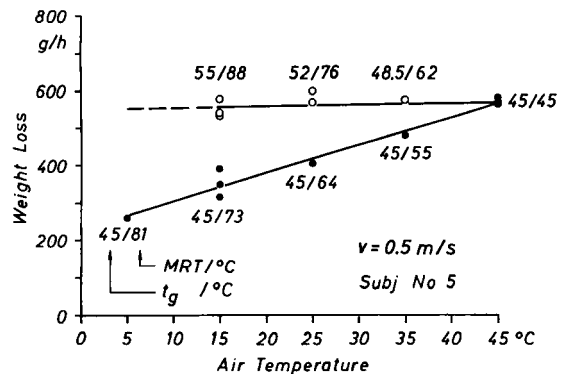


Figure 4. Weight loss of a subject in unequal air and radiant temperatures at a constant globe temperature (t_g) and at globe temperatures elevated stepwise. (MRT = mean radiant temperature, v = air velocity)

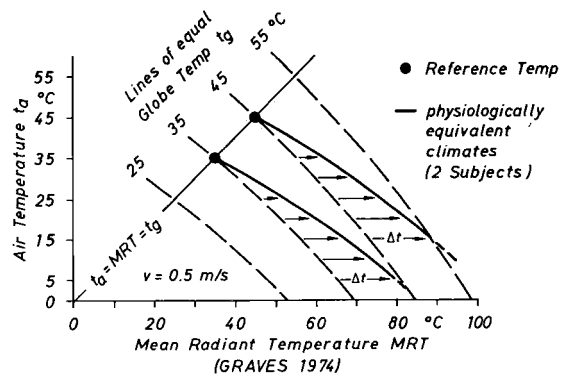


Figure 5. Comparison of some isotherms of Vernon's globe thermometer with lines of physiologically equivalent climates. (Temp = temperature, v = air velocity)

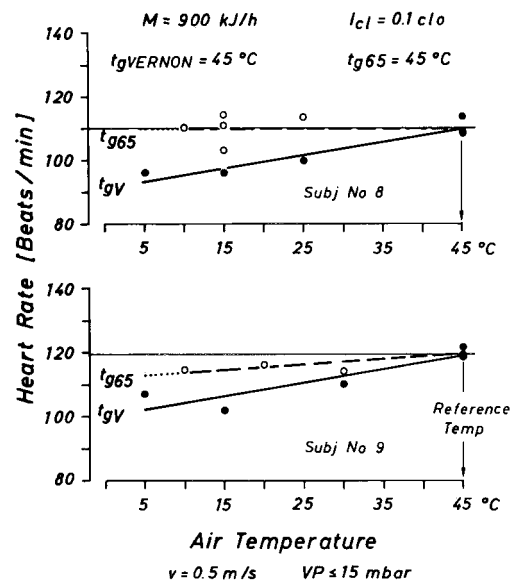


Figure 6. Heart rates of two subjects in different air temperatures at a constant temperature of Vernon's globe thermometer (t_{gv}) and of the modified globe thermometer (t_{g65}). (M = metabolic rate, I_{cl} = thermal insulation of clothing, Temp = temperature, v = air velocity, VP = vapor pressure)

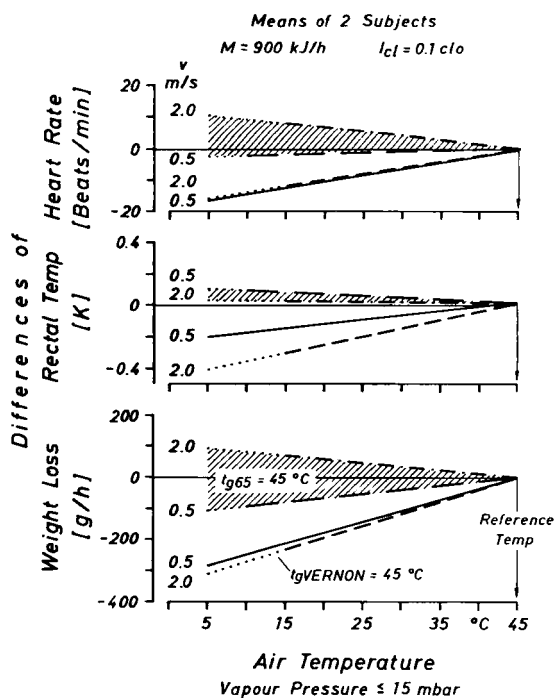


Figure 7. Description of physiologically equivalent combinations of unequal air and radiant temperatures by means of the modified globe thermometer (t_{g65}) at the air velocities of 0.5 and 2.0 m/s. (M = metabolic rate, I_{cl} = thermal insulation of clothing, v = air velocity, Temp = temperature, t_{gV} = Vernon's globe thermometer)

when the air temperatures were lowered. This observation was to be expected from the results of the experiments in series 3. For the other subject (subject 8) the data were practically equal to the data obtained at the reference temperature.

There was henceforth the crucial question of how the physiological responses were influenced by the air velocity of 2 m/s. Figure 7 shows the mean regression lines of the two subjects represented in figure 6 at a constant t_{gV} and a constant t_{g65} with air velocities of 0.5 and 2 m/s. For the sake of clarity, the ordinates in figure 7 have not been made to indicate the absolute values of the physiological response in question, but rather the differences in the values at the reference temperature, as these values differed individually. The results for weight loss demonstrate this comparison in a fairly typical way. The two lowest regression lines, decreasing steeply with a lowered air temperature, refer to experiments in which the t_{gV} was kept constant at 45°C. As has already been mentioned, the sweat loss decreased by about 300 g/h from an air temperature of 45°C to that of 5°C in spite of the constancy of the t_{gV} . The change in air velocity from 0.5 to 2 m/s had no influence. The two other lines refer to experiments at a t_{g65} of 45°C. The upper line, derived from experiments at an air velocity of 2 m/s, increases slightly, whereas the lower line, referring to an air velocity of 0.5 m/s, decreases slightly. This re-

sult was expected from the experiments of series 3. The hatched triangle represents the remaining errors due to changes in air velocity. The heart rate data presented in figure 7 show nearly the same configuration as that of weight loss. For rectal temperature, there was a certain similarity to the findings for weight loss and heart rate, but the differences were fairly small (figure 7).

According to these results, the errors of the t_{gV} could actually be reduced by the simple modification of reducing the diameter of the black globe used. All the physiological data obtained in the experiments of this series were summarized and used for calculating quantitatively the average improvement. It was found that the errors of the t_{gV} were reduced by about 75 % when the mean radiant temperature exceeded the air temperature up to nearly 100 K in the air velocity range of 0.5–2 m/s.

Discussion and concluding remarks

According to similar recent studies, the improvement found with the modified version of Vernon's globe thermometer seems to apply also when subjects are exposed to unilateral instead of circular radiation, perhaps also when heavier work is performed. Additional series of experiments are now being conducted in which men wearing commonly used workclothes are serving as test subjects. The results obtained thus far show that also under these clothing conditions preference should be given to a modified globe thermometer. In a comparison with the values of Vernon's instrument, however, the improvement was smaller than that obtained in the experiments described in this paper. A globe with a diameter slightly smaller than 65 mm might be more suitable for describing combinations of air temperature, mean radiant temperature, and air velocity which are physiologically equivalent to fully dressed subjects. The results which are already available, however, seem to justify the proposal to replace the original globe thermometer of Vernon by a new instrument. This proposal has to be considered with caution, as the effects of various combinations of clothing, work load, individual tolerance, etc. are still incompletely known.

Although the proposal will be helpful to the practitioner in the near future, it should certainly be considered as a temporary solution, there is still an error of 25 %. It seems to be difficult to achieve further improvement however by other modifications under the conditions of the present studies, which are simple and, therefore, acceptable for the practitioner. A simple instrument like a globe thermometer can obviously describe physiologically equivalent combinations of unequal air and radiant temperatures at various air velocities only by approximation.

Anyone who intends to describe and evaluate a climate measures air temperature in degrees centigrade and air velocity in meters per second and uses a psychrometer, for instance, for collecting figures on

air humidity. Curiously, and contrary to this fact, Vernon's globe thermometer was so impressive that, for more than 50 years, the existence of basic physical units of heat radiation have been neglected. A definite solution to the problem can probably be expected only after one liberates oneself from the fascination of a primitive instrument which is supposed to be able to integrate the effects of all the thermal factors resulting in the final reaction of the complicated human body.

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Heat stress in protective clothing

Interactions among physical and physiological factors

by Sarah A Nunneley, MD¹

NUNNELEY SA. Heat stress in protective clothing: interactions among physical and physiological factors. *Scand J Work Environ Health* 1989;15(suppl 1):52-57. Data from experiments on animals and humans have supported the development of computer models that predict human response to various combinations of the three main heat stress factors work, clothing, and environment. However, recent application of such models shows that the validity of their output is limited in part by the need to represent more faithfully the interactions among the primary heat stress factors and certain physiological variables. Examples of such interactions include the weight and stiffness of protective outfits increasing the metabolic cost of a task, profuse sweating that wets clothing and alters its heat transfer characteristics, task-related movements altering air exchange rates through clothing, individual aerobic capacity affecting thermoregulatory response to a given metabolic load, and sweat retention in clothing raising skin wettedness and possibly inducing sweat suppression. This paper reviews recent research in these areas and identifies certain areas where further data are needed.

Key terms: clothing, computer models, sweat, thermal stress, work.

Modern civilization seems to provide ever more reasons for people to work in hostile environments requiring them to wear special clothing for protection from the effects of hazards such as hypoxic atmospheres, toxic chemicals, and mechanical forces. Unfortunately, the clothing and associated respiratory equipment often create a heat stress problem, the seriousness of which ranges from discomfort to impaired performance, illness, collapse, and even death. The effects of work in heavy, impermeable clothing have been illustrated well by studies on men wearing firefighter outfits under mild and hot conditions (1-3).

Heat balance is possible only when the sum of the environmental and metabolic heat load on the body is matched by outward heat flow to the environment. The physical processes involved are understood well, as are simple clothing effects on convective, radiative, and evaporative heat exchange. A number of authors have developed predictive equations and charts for heat stress [eg, Kenney et al (4), Shapiro et al (5), and Vogt et al (6)]; yet it is often difficult to predict reliably the heat stress and strain which may result from a given combination of conditions. More complex computer models are also used, as reviewed by Lotens (7). But they often disagree, and it is still necessary to check their output against data from human subjects (8). In our laboratory my colleagues and I are using both the Texas model (9) and that of the US Army Research Institute for Environmental Medicine (10) to explore the effects of semipermeable and impermeable cloth-

ing on personnel working under a range of climatic conditions (11). Comparison of computer model output with experimental results reveals certain systematic errors, such as a tendency to underestimate the amount of sweat which will evaporate from subjects engaged in treadmill walking while dressed in heavy ensembles.

The validity of output from computer models is limited by their failure to simulate adequately the more complex, second-order effects of clothing on heat balance. Specifically, an improved understanding is needed of the interactions among the environment, the clothing, the wearer, and the task being performed. Figure 1 is a simplified representation of this multidimensional problem. This paper reviews current knowledge on these topics and identifies some areas where further research is needed.

Clothing adds work

Protective clothing increases the metabolic cost of performing a task by adding weight and by otherwise restricting movement. The binding or hobbling effect of multilayered clothing adds measurably to work, eg, treadmill walking in arctic clothing raises oxygen consumption by about 10 % over the value for a lightly clothed subject carrying the same weight (12, 13). Clothing can also require added movement to compensate for problems such as restricted visual fields, failure of communication, or loss of manual dexterity.

The effect of added weight on work load depends in part upon the task, eg, a heavy suit poses little problem for a stationary worker but presents a severe handicap for a firefighter climbing a ladder or stairwell.

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Walking uphill with added weight is considerably more stressful than an equivalent increase in power output induced by steeper climbing (figure 2) (14). Weight distribution is also important, since a load carried on the legs and feet causes a greater increase in metabolism than does the same weight placed on the hands, torso, or head (figure 3) (15). The difference is probably due to the cyclic up-and-down displacement of the lower limbs, which produces internal heat without measurable external work.

Clothing complicates evaporation

Evaporation of sweat normally provides a powerful physiological cooling mechanism for humans under warm work conditions, taking up $0.68 \text{ W} \cdot \text{s}$ (0.58 kcal) of heat for each gram of water vaporized. For a nude subject, environment-driven heat storage should theoretically occur only when E_{req} approaches E_{max} , where E_{req} is the evaporative cooling required to allow human heat balance under a given set of conditions and E_{max} is the maximal amount of evaporation which can be supported by the environment (16). In fact, heat strain in nude subjects occurs at lower values due to the tendency to drip sweat (17). Clothing both inhibits evaporation by creating a humid microclimate and diminishes the cooling effect of the evaporation which does take place, so that thermal strain occurs at E_{req}/E_{max} values which are well below the value for nude subjects.

The resistance of clothing materials to the passage of water vapor can be determined in vitro by techniques analogous to those for measuring thermal insulation using "sweating" heated plates or manikins. The

results are generally expressed as a dimensionless number along a continuum from zero (impermeable) to unity (unclothed control). As with insulation measurements, these static values neglect the effects of body motion and resulting convective exchange between the microclimate and the outside environment. Several laboratories have attempted to remedy these deficiencies by developing techniques to monitor conditions in the microclimate. Holmér & Elnäs (18) drew air sam-

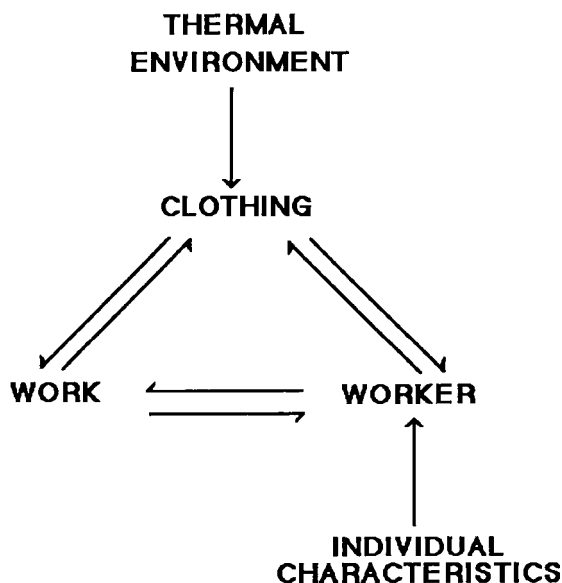


Figure 1. Diagram of heat stress factors. Arrows represent the interactions among the factors which are the focus of this paper.

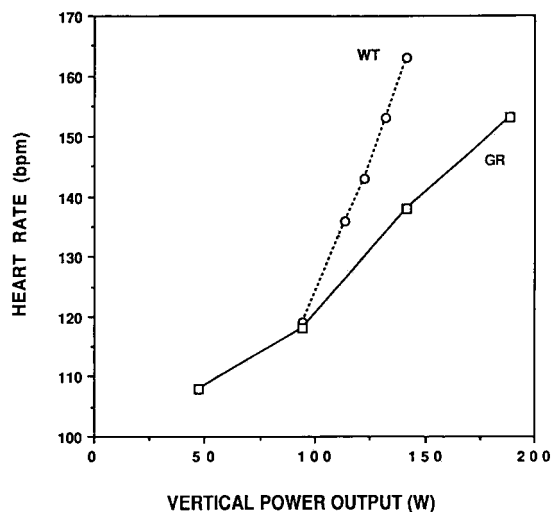


Figure 2. Heart rate plotted against vertical power output. The values are means for ten subjects who walked on an inclined treadmill at 1.34 m/s . The power requirement was increased by raising the treadmill grade (GR) or by adding backpack weight (WT) at a fixed grade of 10 %. Data from reference 14.

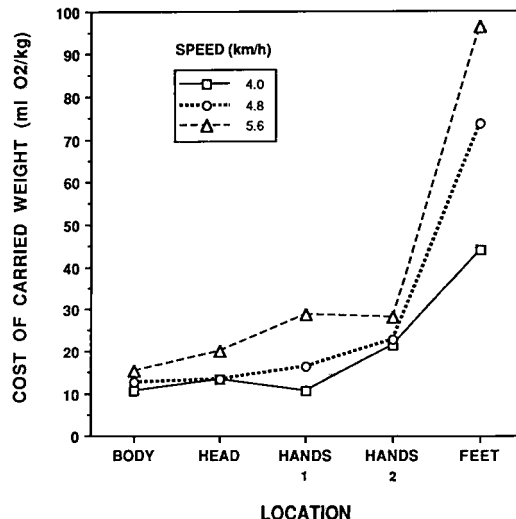


Figure 3. Metabolic cost of weight carried at different sites of the body. The values are means for ten subjects who walked on a level treadmill at the speeds indicated. Hands 1 and 2 represent weights of 4 or 7 kg/hand, respectively. Redrawn from reference 15.

ples from the microclimate and calculated water vapor pressure using general gas equations. Others have determined dewpoints at selected skin sites (19). An alternative approach is to have subjects work at a fixed rate under warm, dry conditions until they reach a thermal steady state, then progressively raise ambient humidity until the core temperature shows an upward inflection, the result being the "critical evaporative coefficient" for the clothing ensemble (20, 21).

Evaporative efficiency (E) is the proportion of secreted sweat which actually evaporates and thus provides potential body cooling. For nude subjects, E is determined from body weight loss if no dripping takes place, or dripped sweat can be quantified after being caught in an oil-filled pan located beneath the subject (22). For clothing studies *in vivo*, the usual technique is to weigh the nude subject and the clothing (or the clothed subject) before and after heat exposure and calculate E as the ratio between clothed weight loss and nude weight loss. The usefulness of this technique is severely limited because it assumes that all secreted sweat either evaporates from the skin or stays in the clothing. Thus the procedure ignores the possibility of external dripage, fails to address the reduction in the cooling effect of evaporation from the clothing rather than the skin, and provides no information on the time course of these processes.

Unfortunately, none of the techniques described can account for the complex realities of heat transfer for a profusely sweating worker in a multilayer clothing system, where secreted sweat may either evaporate at the skin or wick into the clothing and there may evaporate, drip or remain trapped (figure 4). In impermeable suits, sweat may evaporate at the skin, condense on the inner surface of the impermeable layer, and then wet intervening layers and decrease their thermal insulation in the process.

Only sweat vaporized at the skin delivers maximal effect; evaporation from clothing provides reduced body cooling because the site of the phase change is remote from the skin and much of the heat comes from the environment (23, 24).

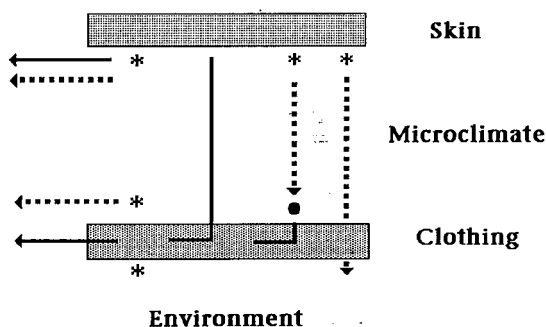


Figure 4. Diagram of pathways for secreted sweat. (Asterisks = sites of evaporation, filled circle = condensation, broken lines = water vapor, solid lines = liquid water)

Impermeable clothing prevents any sweat evaporation and is a potential hazard to the wearer even at moderate environmental temperatures. Provision of ventilation may be of little help, since backpack blowers generally supply only about $28 \text{ l} \cdot \text{min}^{-1}$ of ambient air, insufficient to provide meaningful thermal relief (3). Brown (25) showed that much higher airflows, on the order of $100 \text{ l} \cdot \text{min}^{-1}$, are required to produce effective cooling. Artificially enhanced evaporation from an outer garment could prove useful under some conditions. A wetted cover over an impermeable suit could remove a significant amount of heat given low atmospheric humidity and a generous water supply. The effectiveness of such cooling would also depend upon the presence of minimal insulation between the impermeable layer and the skin.

Movement ventilates clothing

Body movement increases heat exchange through clothing by ventilating the microclimate with ambient air. This "pumping" means that the actual insulation and vapor-barrier characteristics of an ensemble may be much lower than the values measured on a static manikin. The magnitude of pumping depends upon many factors, among them clothing design and fit, external thermal conditions, and body movements. Sealed impermeable clothing virtually eliminates the pumping effect, although motion increases external convection.

The need to quantify pumping led to the development of moving, heated manikins which allow the determination of insulation and vapor transmission while their limbs are swung. Figure 5 shows results from such a manikin both for static standing and for "cycling" on an externally-driven ergometer. The cycling motion reduced measured insulation by about 0.2 clo for each of three conventional clothing combinations (26).

Although moving manikins are helpful, they provide only a minimal simulation of human motion, and several laboratories have attempted to measure pumping on human subjects. An early attempt involved measurement of tracer gas washout curves (27, 28). A more recent technique employs a steady-state measurement in which a stream of tracer gas (carbon dioxide in air) is introduced into the clothing and an equal volume of mixed gas is withdrawn; this procedure permits the calculation of microclimate air exchange without the need to seal the clothing (29). Figure 6 illustrates the effect of treadmill walking and clothing layers on ventilation at the surface of the thigh.

Vogt and his co-workers (30) examined the effect of pumping on subjects pedaling an ergometer. Various components of thermal exchange were teased out with the use of a matrix of environmental conditions which controlled convective and radiant heat exchange. In this case pumping increased convection by about 28 %, much more than on the cycling manikin; the

difference was attributed to the added effect of human respiratory movement, as well as to oscillations of the arms and trunk. They calculated that movement provided an air exchange of about 70 l/min through the microclimate and demonstrated that pumping may reduce radiant exchange when air temperature is close to skin temperature and produce a paradoxical “increase” in insulation (30). Thus the magnitude and even the direction of the pumping effect depend upon specific conditions.

Wearer alters clothing characteristics

Individual factors affecting heat exchange in clothed humans include the fit of the garments and the disposition of any apertures, both of which control the effective insulation by altering convective exchange between the microclimate and the external environment.

Sweat rate is another factor with wide interindividual variation. Sweat-wetting can seriously reduce clothing insulation value and thus improve the linkage between skin and the environment, a change which may be either an advantage or a disadvantage depending upon environmental conditions. In addition, wetting tends to diminish cooling efficiency. When known amounts of water are infiltrated into clothing ensembles, the cooling effect per gram of water evaporated declines progressively as clothing wetness increases (24).

Individual characteristics affect heat strain

Thermal physiologists often distinguish between externally imposed thermal stress and the resulting physiological changes or thermal strain. Response to heat stress is strongly influenced by a variety of human characteristics, making it nearly impossible to predict the heat strain which will occur in an individual exposed to a given set of environmental conditions (31, 32).

While the metabolic cost of carrying weight (ie, work efficiency) is usually treated as constant from one worker to another, the physiological effect of a fixed load varies with the size and physical conditioning of the wearer. A sealed suit with a self-contained breathing apparatus (SCBA) weighing 25 kg represents a 25 % weight increase for a 100-kg person but a 50 % load for a 50-kg subject, and heart rate during work rises directly in proportion to added weight expressed as the percentage of body weight (14). The added work will also use a greater percentage of aerobic capacity in a small person, or in one with low aerobic capacity, and will produce a higher core temperature even in the absence of environmental heat load.

In fact, the assumption of relatively constant work efficiency needs reexamination. Recent studies on subjects pedaling a cycle ergometer have revealed a significant range among individuals (Nadel, personal

communication). The phenomenon of “work load creep” in prolonged experiments is also well known but little studied. It appears likely that high levels of cardiovascular stress and hyperthermia may decrease efficiency and produce an increase in heat production per unit of external work, thus a positive feedback loop being formed.

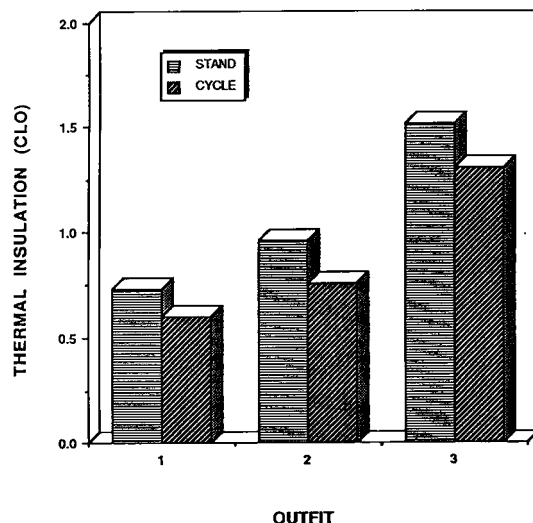


Figure 5. Thermal insulation measured on a heated manikin either standing static or seated on an externally-driven cycle ergometer. Outfits are as follows: 1 = briefs, t-shirt, cotton shirt and trousers, 2 = same as 1 plus jacket, 3 = same as 2 plus “thermo-suit.” Redrawn from reference 26.

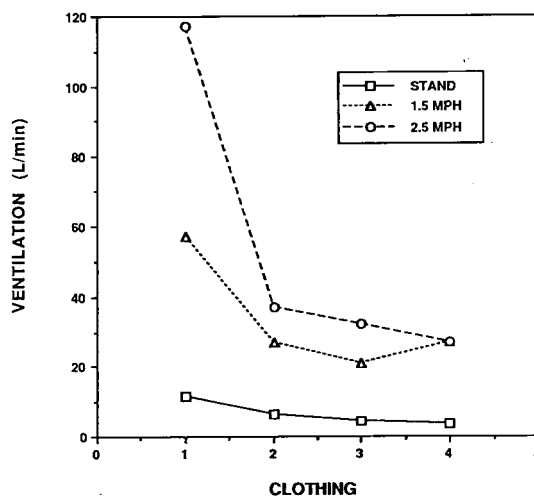


Figure 6. Ventilation at the thigh measured with the subject standing still or while walking on a treadmill at 1.5 or 2.5 miles per hour (mph) (1.5 miles = 2.4 km, 2.5 miles = 4.0 km). The clothing layers over the thigh are as follows: 1 = none, 2 = cotton trousers, 3 = coverall over trousers, 4 = same as 3 with apron added. Plotted from data of reference 29.

Individual sweat rates also affect stress-strain relationships. Sweat-wet clothing next to the skin is not only uncomfortable, but also tends to reduce sweat rates gradually through a process variously known as sweat suppression or hydromeiosis — the divergent names reflecting controversy over the mechanism involved.

Secretion of sweat which fails to provide body cooling produces dehydration and discomfort without thermal benefit. Thus the high sweat rates associated with heat acclimatization may prove a liability for persons wearing heavy clothing. This possibility leads to speculation concerning the possible benefits of artificial sweat suppression, possibly through the use of atropine (24). The benefit could be amplified under some conditions, since atropine not only suppresses sweat secretion, but also increases cutaneous blood flow (33).

Summary and concluding remarks

Clearly there is much yet to be learned about the physical and physiological aspects of thermal exchange in protective clothing systems. A better understanding is needed of the interactions between the environment, clothing, task, and worker to support the development of predictive models which are valid over the entire spectrum of thermal conditions encountered among industrial and military applications. Particularly challenging areas needing improvement include the following: (i) representation of intermittent or changing work load and/or environmental conditions, (ii) quantification of cumulative effects due to dehydration and fatigue, (iii) changes to the metabolic cost of real-world tasks due to clothing, worker characteristics, thermal stress and fatigue, (iv) quantification of pumping effects with respect to interactions between clothing, tasks and the environment, (v) physiological effects on tolerance for work in protective clothing, including the roles of aerobic fitness, strength training and heat acclimatization, (vi) characterization of sweat-related heat exchange in complex clothing systems, especially with regard to continued sweat production, progressive wetting of clothing layers, evaporation from outer layers, and drippage, (vii) the possible role of natural or artificially-induced sweat suppression, and (viii) the relationship between heat storage (core temperature) and heat casualty incidence (which requires an improved understanding of relevant physiological factors and the epidemiology of human heat illness).

One potential pitfall to be avoided in modeling is the temptation to produce specific predictions which look impressive but are not adequately supported by data. For instance, it is hardly appropriate to output estimated tolerance time limits to the nearest minute when other components of the model produce an error range of several percentage points. Any use of models should clearly differentiate among predictions which lie in the thoroughly validated sector as opposed to

those which represent scanty validation or speculative extrapolation from known conditions.

The rewards of better understanding of these areas should include the ability to identify critical experimental parameters, to predict hazardous conditions, and to minimize human experimentation. The ultimate beneficiaries will be those whose work takes them into environments which test the limits of human capacity to perform useful work under hazardous or hostile conditions.

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Recent trends in clothing physiology

by Ingvar Holmér, PhD¹

HOLMÉR I. Recent trends in clothing physiology. *Scand J Work Environ Health* 1989;15(suppl 1):58—65. The need for high-performance protective clothing systems in space, polar, and underwater operations and in industrial environments has stimulated research in clothing physiology. New, sophisticated measurement methods, some of which are going to be international standards, have facilitated this research. Measurements with subjects have validated manikin data, but have also provided information about the dynamic character and the individual variability of thermal properties of clothing under conditions encountered in the field. Manikin measurements of the basic thermal properties of clothing (insulation and evaporative resistance) have to be corrected to apply to the user situation, due to the effects of wind, posture, body movement, and moisture absorption. Evaporative heat transfer is better defined and should be incorporated in heat exchange models and thermal indices. Important aspects of clothing physiology remain to be investigated.

Key terms: climate, evaporative resistance, insulation, methods, models, physiological reactions, thermal comfort.

Clothing is the fundamental and simple instrument by which man regulates his body heat exchange and adjusts thermally to the environment. Most people rely on their own experience when they select their clothing. This practice presents few problems when conditions are not extreme and the garments are made of conventional materials. However, as more people participate in outdoor activities, workers are exposed to more and more extreme environments, and the market is flooded with textiles, fabrics, and clothing with new, “super” properties, it is more difficult to make the right choice.

Clothing research has its own history, but it is evident that the last decade has seen a rapidly growing interest in clothing research, particularly in terms of the thermal function of clothing. This growing interest is indicated also by the number of conferences which have addressed the special problems of protective clothing (Stockholm 1981, Lyon 1983, Raleigh 1984, Tampa 1987). These environmental ergonomics conferences have included several sessions devoted to clothing research.

Although physiologists love to investigate nude subjects and, thus, circumvent many of the problems caused by clothing, an adequate assessment of the effects of climate, for practical purposes, must include the impact of clothing. This necessity was pointed out by Wissler (1), who concluded that one of three major factors limiting the currently available models for analyzing human responses to environmental stress and exercise is the “inadequate description of the clothing worn by the subject [p 272].” This presentation

is a review of some recent research in clothing physiology.

Terminology

The effect of clothing on heat exchange is determined by its thermal insulation and evaporative resistance (or permeability index). Methods are available for determining these properties. However, it is important that they be standardized on an international basis, and this work is in progress (2). The standard values for the thermal properties of clothing are the basic insulation (I_{cl}) and the basic evaporative resistance (R_{ecl}) (or permeability index, i_{cl}). Other types of insulation and resistances are presented in table 1. The total insulation (I_t) is the sum of clothing insulation and boundary air layer insulation (I_a/f_{cl}), corrected for the increased body surface area caused by clothing. Often clothing is worn under dynamic and transient conditions which differ from the “standard” conditions under which the basic values were obtained. Accordingly, in practice, the resultant insulation ($I_{cl,r}$) and the resultant evaporative resistance ($R_{ecl,r}$) differ from the basic values. In most cases the resultant values are lower than the basic values. This difference is caused by the effect of wind, body movements, and moisture condensation and absorption on microclimate ventilation. This subject will be discussed further in a later section.

Conventional physiological studies

Several physiological studies have reported the imbalance that occurs when subjects are exposed to extreme combinations of climate (often heat), work, and clothing (particularly protective clothing) (3—17). Un-

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fortunately, some of the studies do not report the thermal properties of the clothing worn and/or are designed in such a way that it is difficult to generalize the results and apply them to other than the investigated conditions. Comprehensive studies of occupational exposure to work in cold storage have been carried out (18, 19). Problems with traditional work clothing were reported, and the difficulties involved in adjusting the clothing to variation in activity and temperature in short periods of time were pointed out. Another major problem in this branch of research is extremity cooling and inappropriate protective gear for hands and feet.

Measurement of clothing heat exchange

Detailed analyses of clothing heat transfer are difficult in experiments with subjects. The investigator is left with partitional calorimetry, which allows quantitative measurements of whole-body dry and evaporative heat exchange. These kinds of measurements are, however, an important complement to the increasing number of manikin data, since they (i) validate the measurements with thermal manikins, (ii) give resultant values for comparison with basic values, and (iii)

show individual variability in heat exchange patterns with clothing.

Several investigations have reported considerable variation between manikin data and the data obtained with partitional calorimetry (6, 8, 20–28). Most of the differences can be explained by the pumping effect on the microclimate. This effect will be discussed later.

The development of new thermal manikins with multi-sectional, computerized heat regulation allows measurements of local heat flow and is valuable for the assessment of garment design and the composition of clothing systems (24–27, 29). Moveable manikins have contributed to the knowledge of ventilation effects and how resultant insulation differs from basic insulation under the type of movements that can be simulated by the manikin (30). The market for thermal manikins in research is increasing. The ultimate goal of a joint Scandinavian project is to construct a sweating, thermal manikin (31).

The lack of small, reliable humidity sensors have long hampered the studies of vapor transfer and evaporative heat exchange in clothing in vivo. However, several techniques are now available for the determination of vapor pressure at the skin surface and in clothing layers (21, 32). It is possible with such sen-

Table 1. Thermal properties of clothing and air — symbols, units, and definitions.

Term	Symbol	SI Unit ^a	Definitions
<i>Clothing</i>			
Basic insulation	I_{cl}	$^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Insulation of clothing alone under standard conditions (thermal manikin)
Resultant insulation	$I_{cl,r}$	$^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Insulation under actual conditions
Basic evaporative resistance	R_{ecl}	$\text{kPa} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Evaporative resistance under standard conditions
Resultant evaporative resistance	$R_{ecl,r}$	$\text{kPa} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Evaporative resistance under actual conditions
Permeability index	i_{cl}	No dimension	Permeability of clothing layers (fabric layers) under standard conditions
Permeability index	$i_{cl,r}$	No dimension	Resultant value under actual conditions
<i>Air</i>			
Air insulation	I_a	$^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Insulation of boundary air layer under standard conditions (thermal manikin)
Resultant air insulation	$I_{a,r}$	$^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Insulation of the boundary air layer under actual conditions
Basic evaporative resistance	R_{ea}	$\text{kPa} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Evaporative resistance under standard conditions
Resultant evaporative resistance	$R_{ea,r}$	$\text{kPa} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Evaporative resistance under actual conditions
Permeability index	i_a	No dimension	Basic value under standard conditions
Permeability index	$i_{a,r}$	No dimension	Resultant value
<i>Clothing and air layer</i>			
Total insulation	I_T	$^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Basic insulation plus basic boundary layer insulation under standard conditions, $I_{cl} + I_a/f_{cl}$
Resultant total insulation	$I_{T,r}$	$^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Total insulation under actual conditions, $I_{cl,r} + I_{a,r}/f_{cl}$
Total evaporative resistance	R_{eT}	$\text{kPa} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Total evaporative resistance of clothing and boundary air layer under standard conditions
Resultant evaporative resistance	$R_{eT,r}$	$\text{kPa} \cdot \text{m}^2 \cdot \text{W}^{-1}$	Total evaporative resistance under actual conditions
Permeability index	i_m	No dimension	Permeability of clothing and boundary air layers under standard conditions (thermal manikin) (Woodcock i_m)
Permeability index	$i_{m,r}$	No dimension	Resultant value

^a Insulation is often expressed in clo units, 1 clo = $0.155^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1}$.

sors to measure directly the skin wettedness factor, particularly local values. This possibility opens up a new field of research on factors determining evaporative heat exchange and thermal comfort.

Thermal insulation

The basic insulation of a garment or clothing system (I_{cl}) is measured under standardized conditions with a thermal manikin (2). The manikin is static, standing in a climatic chamber at a very low air velocity (v_a) ($<0.15 \text{ m} \cdot \text{s}^{-1}$). Due to wind, moisture absorption, and the movement and posture of the wearer, the resultant insulation ($I_{cl,r}$) provided by the garment, when used, is often less than I_{cl} . This subject has been extensively studied by Olesen and his co-workers (25, 26, 30). They carried out a series of experiments on different types of garments with a moveable manikin and with subjects. They found that (i) I_{cl} is reduced by the effect of wind and body movements, (ii) I_{cl} was reduced by 5–26 % depending on the air permeability of the outer fabric layer, (iii) I_{cl} was reduced by 14–18 % during bicycling and by 5–46 % during walking compared to standing, garment design being an important determinant, and (iv) insulation values measured with subjects were comparable to manikin values for the same clothing ensembles and activities.

Similar studies have been carried out by Umbach (27, 33) and Mecheels & Umbach (24). These researchers have developed a standardized technique for evaluating clothing systems which includes an investigation of the pumping effect.

It is important to realize that the basic insulation value, considered as a characteristic of a garment, does not provide a straight answer as to the protective value of a garment against dry heat loss. This factor is of particular importance in cold environments. The I_{cl} value provided with a clothing ensemble has to be corrected according to the conditions of use to give a more realistic value of its resultant insulation. Unfortunately, the information on this subject is limited, and more work is required. Whenever required insulation or evaporative resistance is computed with a mathematical model, the values are resultant. Selection of appropriate clothing, on the other hand, is made with the basic values, which, therefore, must be corrected to a resultant value.

Evaporative heat exchange

The inability of most heat exchange models to predict, accurately, the effects of wearing protective clothing is a good indicator of the lack of important knowledge about evaporative heat transfer mechanisms. However, this subject has interested many scientists in recent years, and new methods have facilitated the investigations. There are at least three different approaches to the determination of the resistance to

evaporative heat exchange by clothing. It can be based on permeability indices, a permeation efficiency factor, or a direct measurement of evaporative resistance. Evaporative heat exchange is calculated by

$$\begin{aligned} E &= (p_{sk} - p_a)/R_{e,T} \\ &= (p_{sk} - p_a) 16.7 f_{cl} \cdot h_c \cdot F_{pcl} \quad (\text{equation 1}) \\ &= (p_{sk} - p_a) 16.7 i_m/I_{T,r} \end{aligned}$$

where $p_{sk} - p_a$ is the vapor pressure between the skin and the environment in kilopascals. The other factors are discussed in the next two sections. (See also table 1.)

Permeation indices

The first introduction of a permeability index was made by Woodcock (34). His permeability index (i_m) has been extensively used by Goldman and his co-workers (20, 25, 36) and Umbach (27, 33). A more general approach to the analysis of vapor transfer in clothing systems has been applied by Lotens & Van de Linde (37) and Oohori et al (38), who introduced a permeability ratio for clothing layers (i_{cl}) and for the boundary air layer (i_a). The rationale behind and the relationship between the different permeability indices and the permeation efficiency factors has recently been demonstrated (38). All permeability indices are defined by the ratio between the Lewis number for the layer and the Lewis number for an air layer of equivalent thickness. The latter number is a constant and averages 16.7 in this temperature range. The index values vary between 0 and 1 and are dimensionless. The indices are defined and presented in table 2.

Evaporative resistance

Evaporative resistance may be directly measured with subjects by partitional calorimetry and measurements of the vapor pressure gradient between the skin and the environment (21, 32). An example is illustrated in figure 1. With the use of the continuous body weight change and vapor pressure measurements, the total evaporative resistance ($R_{e,T}$) can be determined. The technique is not suitable as a standard, but it gives valuable information about the variation between individuals and garments. It is also suitable for the analysis of the resultant values. Examples of values obtained with this technique are given in table 3 (39).

The standard approach to calculating evaporative heat exchange is to use the i_m index (21, 33, 36) or the permeation efficiency factor (F_{pcl}) (40–42):

$$\begin{aligned} R_{e,T} &= 1/(16.7 f_{cl} \cdot h_c \cdot F_{pcl}) \\ &= 0.06 I_{T,r}/i_m \quad (\text{equation 2}) \end{aligned}$$

The F_{pcl} factor is dimensionless, varies between 0 and 1, and defines the reduced efficiency of evaporative heat exchange caused by clothing (41). The basic formula presents F_{pcl} as a function of basic clothing insulation (I_{cl}) and the convection coefficient (h_c). This relation is valid for light, porous clothing, and

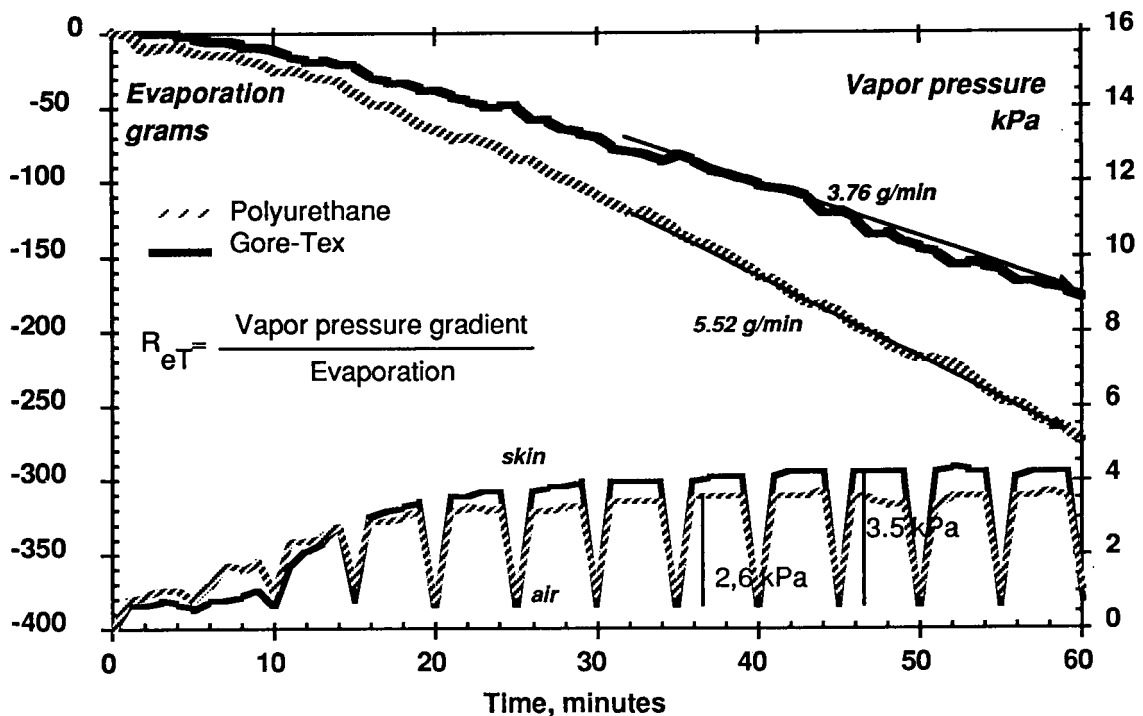


Figure 1. Determination of the evaporative resistance of clothing from continuous measurements of evaporative heat loss (sweat loss) and skin to the ambient water vapor pressure gradient. The results are from one subject bicycling for 60 min in impermeable and semipermeable rainwear (32).

Table 2. Permeation ratios for water vapor transfer through layers of clothing and air. For an explanation of the symbols see table 1. R_{eci} is the evaporative resistance of clothing (or fabric) layers, excluding the boundary air layer.

Layer	Index	Definition	Lewis number	Measurement
Air	i_a	h_a/h_c	16.7	—
Clothing/fabric	i_{cl}	$0.06 i_{ci}/R_{eci}$	i_{ci}/R_{eci}	"Wet" plate or "wet" manikin
Clothing and air	i_m	$0.06 i_T/R_{eT}$	i_T/R_{eT}	"Wet" manikin

Table 3. Thermal properties of clothing ensembles from various sources (9, 29, 32, 39). The R_{eT} values were calculated on the basis of equation 15 from table values. The i_{ci} values were reported by Oohori et al (38). For an explanation of the symbols see table 1. (KSU = Kansas State University)

Clothing	i_{cl} (clo)	i_T (clo)	i_m^a	i_{cl}^a	R_{eT} ($\text{Pa} \cdot \text{m}^2 \cdot \text{W}^{-1}$)
<i>Basic, manikin data</i>					
None (ie, manikin nude)	0	0.8	0.47	0	17
Cotton shirt and trousers (KSU uniform), underwear, socks, shoes	0.65	1.25	0.39	0.32	30
Coverall, T-shirt, underwear, socks, shoes	0.84	1.41	0.39		34
Cotton shirt and pants, underwear, T-shirt, belt, socks, shoes	1.00	1.51	0.32	0.27	44
<i>Resultant, subject data</i>					
Coveralls, long underwear, socks, shoes	0.84	1.5 (1.2 ^b)	0.59 ^b		19 ^b
Rainwear (Goretex [®]), coveralls, long underwear, socks, shoes	1.29	1.9 (1.3 ^b)	0.36 ^b		34 ^b
Rainwear (nylon coated with polyurethane), coveralls, long underwear, socks, shoes	1.29	1.9 (1.3 ^b)	0.16 ^b		77 ^b
Chemical protective suit (impermeable), coveralls, long underwear, socks, shoes	1.4	1.9 (1.1 ^b)	0.06 ^b		180 ^b

^a No dimension.

^b Obtained with measurements on subjects during work in a climatic chamber (9, 32).

the permeability properties of the garments are not considered (41):

$$F_{pcl} = 1/(1 + 2.22 \cdot f_{cl} \cdot h_c \cdot I_{cl}). \quad (\text{equation 3})$$

A more general definition of the F_{pcl} factor, including the i_{cl} factor, is (38):

$$F_{pcl} = 1/(1 + f_{cl} \cdot h_c \cdot I_{cl}/i_{cl}). \quad (\text{equation 4})$$

R_{ct} may now be expressed in terms of I_{cl} , h_c , and i_{cl} . Calculating F_{pcl} is not required:

$$R_{ct} = R_{ca} + R_{cct} = [0.06/(f_{cl} \cdot h_c)] + (0.06/i_{cl}) \cdot I_{cl}. \quad (\text{equation 5})$$

It follows from equations 3 and 4 that i_{cl} in equation 3 is a constant, ie, $1/2.22 = 0.45$, which is a typical value for normal, porous, indoor clothing (38).

It follows from equation 5 that R_{ct} increases rapidly with low index values and with increased insulation. Accordingly, evaporative heat loss decreases at a given vapor pressure gradient (equation 1). A constant value for i_{cl} can therefore not be used whenever clothing with lowered moisture permeability is used. It is recommended that predictive models and indices, based on the original F_{pcl} formula, be modified to include i_{cl} . More work, however, is required to validate this approach, particularly for protective clothing. Values of R_{ct} , i_{cl} , and i_m are given for different types of clothing in table 3.

The permeability index of a clothing system, i_m , is measured with a "wetted" thermal manikin (20, 35, 36), and the permeability index for clothing fabric layers, i_{cl} , is measured with a "skin model" or a "wetted" manikin (27, 37, 38).

Microclimate ventilation

As already mentioned, the variability in the thermal properties of clothing is related to the ventilation of the air in and between clothing layers. The combination of garment design and body movements causes air to be pumped in and out through garment openings and through the fabric. The more impermeable clothing is, the more important this pumping effect is in enabling some kind of "evaporative heat loss." The trace gas technique, first developed by Birnbaum & Crockford (43), has been useful in the evaluation of microclimate ventilation. It is a fast, and simple, method that can be used for analyzing the effect of garment design and different types of work movements (44, 45). Figure 2 shows a theoretical calculation of required ventilation for a garment ensemble of different permeability (46). The required evaporation rate was 120 W (180 g · h⁻¹). It is evident that (i) with lowered permeability, the ventilation requirement increases rapidly, and (ii) in the cold much more ventilation is required at the same permeability to prevent condensation.

Clothing in mathematical models and thermal indices

It was stated already in the introduction that the lack of an adequate description of clothing was a limitation to predictions of thermal effects with mathematical models (1). Indeed, most climate indices do not consider the thermal properties of clothing and, therefore, only apply to normal everyday clothing. The wet bulb globe temperature (WBGT) index (47) is such an index; it requires special correction to be used with special clothing (48).

Most rational climate indices, including the proposed new standard of the International Organization for Standardization (SW_{req}) (2), use the original F_{pcl} format for calculating evaporative heat exchange. As previously pointed out, this is a special case, applicable only to light, porous everyday clothing, and should be replaced by the general format based on the moisture permeability of clothing (i_{cl}).

The same situation is valid for the effective temperature (ET*) index (42). A recent modification of ET* takes into consideration the general equation (40). This version is the most sophisticated climate index so far, in terms of incorporating the moisture permeation properties of clothing. However, the experimental validation of this method for less impermeable garments has yet to be done.

In the comfort zone the predicted mean vote (PMV) index (55) takes thermal insulation but not moisture permeability into account. This is a small problem, since the field of application of the method is mostly at low activities requiring none or little sweating. If, however, it is applied to higher activities with special clothing, the error might be significant, as the evaporative heat exchange is overestimated. A correction of the method can be made to account also for such conditions (40, 50).

Few climate indices are available for cold environments. Required insulation (IREQ) has been proposed as a method for assessing cold stress (51). In this model clothing heat exchange is based on both clothing insulation and evaporative resistance.

If values for both insulation and evaporative resistance (permeability) are incorporated in the existing models and indices, their field of application becomes wider and the predictive power increases. It should be emphasized, however, that, despite the introduction of the i_{cl} index, several problems remain as to a correct description of the impact of clothing on evaporative (and conductive) heat exchange. The thermal properties of clothing previously described (I_{cl} and i_{cl}) relate to a standard condition, but clothing is worn under different conditions. The problems are related to the effects of wind, wear movement, and moisture absorption, all of which affect the microclimate and thermal properties. In other words, the resultant insulation and evaporative resistance under the actual wearing conditions are likely to be different from (in most

cases lower than) the basic values. With a few exceptions little attention has been paid to these problems.

There are two ways to proceed. One is to stay with the present set of equations to describe heat exchange and realize that resultant values for clothing are required. Since thermal properties are unique for each garment, this method requires correction factors to translate basic values to resultant values. This school is well represented by Goldman and his co-workers (20, 35, 36) and the Hohenstein group (24, 27, 33). Goldman determines "pumping coefficients" for each garment ensemble to derive its "effective" (= resultant) value. Mecheels & Umbach (24) have developed a technique by which each garment is measured during dynamic conditions, ie, with a "walking" manikin. The values obtained during this measurement are used in their prediction model and serve as a kind of correction. Indeed, with this approach, more effort should be spent analyzing how basic values change under different wearing conditions.

The other approach requires the development of equations which describe, in a general format, the impact of, eg, wind, posture, body movement, etc. The concept of a relative air velocity (v_{ar}) is in line with this approach. However, the equation used by most models [$v_{ar} = v_a + 0.0052 (M-58)$] (2) needs better validation for different types of activity. More work is required on this subject.

Clothing and comfort criteria

Of great importance for the assessment of the thermal impact of a clothing system are the physiological criteria. What is thermal comfort? What is physiologically acceptable? What are the tolerance limits? The physiological factors operating in all heat exchange models are mean skin temperature and sweat loss. With respect to mean skin temperature, the comfort criteria (52) appear to apply also to cold conditions (8). The sweat loss may be expressed in terms of a required evaporative heat loss (52) or as a required skin wettedness (40, 41). The concept of a required evaporative heat loss does not apply to cold conditions (8) or when special clothing is worn (eg, protective clothing) (37, 40, 50). The moisture permeability of clothing is not considered with this approach. Skin wettedness is related to the sensation of comfort or, preferably, warm discomfort (40). With the skin wettedness approach the moisture permeation properties of clothing can be included.

Nonthermal factors

Several investigators have shown that the perception of comfort and the acceptance of a garment does not only depend on thermal factors (53—55). Garment fit, moisture buffering properties, and mechanical proper-

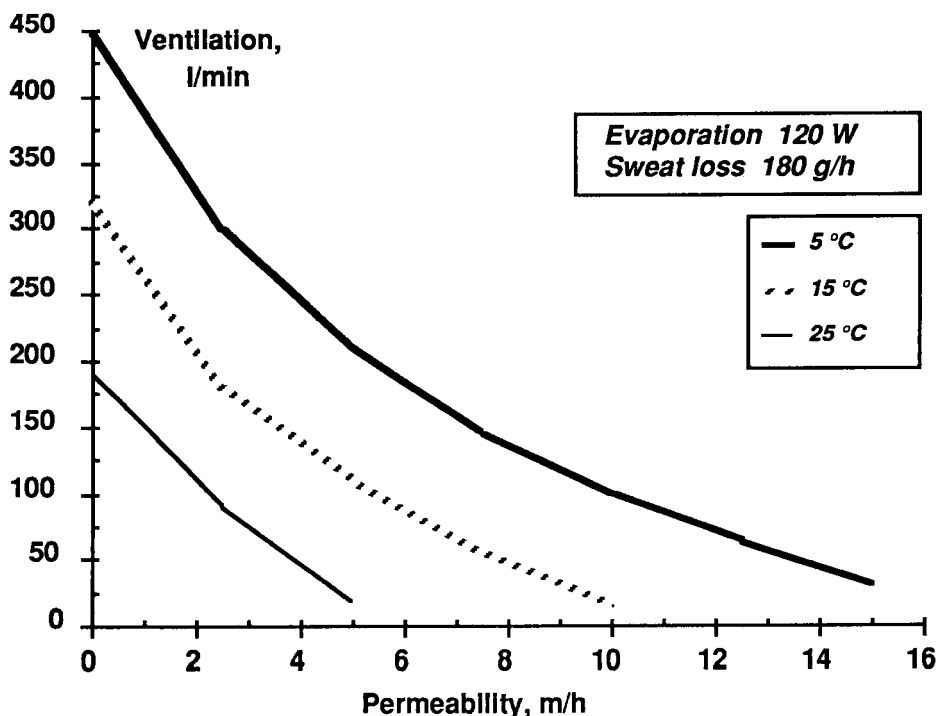


Figure 2. Required ventilation rates at three ambient temperatures as a function of permeability to prevent condensation. The values were calculated for a garment ensemble, and the required evaporation was 120 W (180 g · h⁻¹) [modified from Lotens (46)].

ties of fibers and fabrics are correlated with the sensation of comfort. Umbach (27, 33) has extensively studied the moisture buffering capacities of underwear of different material and developed test methods that measure relevant properties. Gwosdow et al (53) found that the friction between the fabric and the skin increased sharply when wettedness was 0.25–0.30. More work is required to investigate the interrelationship between thermal and nonthermal factors and their importance for thermal sensation.

Future research

Several aspects of the thermal function of clothing have been reviewed, and some areas have been identified as poorly integrated or understood due to lack of knowledge. Some of the most significant problems to be investigated in both chamber and field experiments may be summarized and conclude this review of recent trends in clothing physiology: (i) the variability in the thermal properties of clothing under wearing conditions (wind, posture, effects of body movements, etc.), (ii) the effects of moisture absorption and the condensation and reevaporation of sweat in clothing, (iii) the effect of clothing on heat exchange during transient conditions (changing climate, intermittent activity, etc), (iv) the effects of nonuniform clothing distribution, (v) the validation of predictive models for special clothing (eg, protective clothing), (vi) the validation of predictive models with basic and resultant values, respectively, for the thermal properties of clothing, (vii) the validation of different physiological criteria for the assessment of comfort, acceptance and tolerance to all thermal environments, and (viii) non-thermal factors and their effects on clothing function and comfort.

Acknowledgments

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The actual insulation of multilayer clothing

by Wouter A Lotens¹

LOTENS WA. The actual insulation of multilayer clothing. *Scand J Work Environ Health* 1989;15(suppl 1):66-75. The effect of geometric factors on insulation was calculated mathematically for standing humans. It was found that internal radiative heat transfer in an ensemble was significant for insulation, that intrinsic clothing insulation is a useful concept only for indoor climates, and that shape plays a minor role. The literature agrees closely on insulation and clothing surface area figures, and the latter are compatible with model predictions. Finally, it was shown that wind, body motion, the effects of posture, and the fit of garments are predictable. Sitting provides more insulation than standing for light clothing, but the reverse is true for heavy clothing. Insulation is decreased by about 20 % by cycling and by about 40 % by walking, and a reasonable estimate can be made of the effect of wind and wind and motion together. The effect of air motion on vapor permeability is stronger than the effect on heat transfer.

Key terms: activity, clothing, fit, insulation, manikin, model, posture, subjects, vapor permeation, wind.

Clothing is usually regarded as a single homogeneous layer, covered with an air layer. However, this is too much of a simplification for general considerations on actual clothing insulation. First, in reality, the number of layers varies over the body. The trunk is usually covered with more layers than the extremities, so that insulation is not uniform over the body, particularly for the head and hands, which are often uncovered. Second, the various fabric layers encapsulate the human body, the outermost layers having less effective insulation due to their increased surface area. The ensemble contains more air than fabric and will show radiative heat transfer, in particular for loosely fitting clothing. Third, the enclosed amount of air changes with the posture of the wearer, since clothing is tightly stretched over specific body areas when a person sits but is freely hanging during standing. The enclosed air may also change during motion of the wearer (pumping) and due to wind penetration through the fabric or through apertures (ventilation). There is also an interaction between the fit of the clothing and these air exchange effects.

In the present report these effects have been addressed in detail, and literature data have been compiled to show that there is more consistency in respect to these effects than has been generally recognized. Thus the available data banks of clothing insulation values, such as provided by McCullough et al (1), may be extrapolated to clothing insulation in a wider range of environments and activities. The effects of interaction between heat and moisture transfer (absorption, condensation), which are very significant for actual in-

sulation as well, are beyond the scope of this paper however.

From fabric to clothing

The various layers of clothing are draped in a special way. Underwear is often tightly fitting, due to stretchability, but trousers, shirts, sweaters, dresses, etc, typically hang loosely, trapping layers of air. In a first approximation it will be assumed that these air layers are uniform over the body, although it is clear that this assumption is not realistic for the shoulder and hip areas, where the clothing layers are in close contact, and in many other areas where pleats and folds shape air chambers rather than layers. Because of the radiation component, the conductivity of the enclosed air changes with its thickness, according to the following equation:

$$\lambda_a = 0.026 + 5 \cdot \text{tha} \quad (\text{W} \cdot \text{m}^{-1} \cdot ^\circ\text{C}^{-1}), \quad (\text{equation 1})$$

where tha is the average thickness (m). The first term on the right represents pure conduction and the second term is radiation.

Siple & Cochran (2) used a tape measure method to determine the thickness of clothing ensembles and compared the thickness with the actual clothing insulation, determined on a heated manikin. They found a conductivity of $0.040 \text{ W} \cdot \text{m}^{-1} \cdot ^\circ\text{C}^{-1}$, which later became Burton & Edholm's (3) famous 4-clo-per-inch rule of thumb ($1 \text{ clo} = 0.155 \text{ } ^\circ\text{C} \cdot \text{m}^{-2} \cdot \text{W}^{-1}$). Since fabric layers per se typically have a conductivity of $0.042 \text{ W} \cdot \text{m}^{-1} \cdot ^\circ\text{C}^{-1}$, the enclosed air in Siple & Cochran's ensembles must have also had a conductivity of about $0.04 \text{ W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$, a value which compares to a size of 3 to 4 mm. In view of the much larger air chambers that have been observed, this seems to be a surprisingly low conductivity. In the laboratory of my co-workers and I a variety of work ensembles

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has shown higher conductivities on the average (4). At locations with a tight fit (chest and back) the conductivity was 0.047 (SD 0.008) $\text{W} \cdot \text{m}^{-1} \cdot ^\circ\text{C}^{-1}$, at locations with a normal fit (buttocks, stomach) it was 0.084 (SD 0.010) $\text{W} \cdot \text{m}^{-1} \cdot ^\circ\text{C}^{-1}$, and at locations with a loose fit (calf) the value was no less than 0.143 (SD 0.015) $\text{W} \cdot \text{m}^{-1} \cdot ^\circ\text{C}^{-1}$. Therefore, in most cases, the radiation component of clothing conductivity dominates over pure conduction, in contrast to fabrics, for which conduction has the largest contribution. Apparently the effect of drape (loose or tight fit) must be considered in more detail.

Another typical difference between fabrics and clothing is that the thickness of a clothing ensemble is usually not uniform. The extremities are less insulated than the trunk. A third point is that the human shape resembles a collection of cylindrical components rather than a flat surface. The effect of the geometric factors drape, body shape, insulation distribution, and partial skin coverage on total clothing insulation can be investigated theoretically by means of a model in which a human is represented by a number of cylindrical elements.

The heat transfer coefficient of a cylinder of radius R_o covered with material with a conductivity of λ_{cl} up to radius R , is given by:

$$h_{cl} = \lambda_{cl} / [R_o \ln (R/R_o)] \quad (\text{W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}). \quad (\text{equation 2})$$

The heat transfer coefficient of the surrounding air, normalized to the skin area, is:

$$h_a = (R/R_o) (h_r + h_c) \quad (\text{W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}). \quad (\text{equation 3})$$

These two heat transfer coefficients in series result in:

$$h = [\lambda_{cl} R (h_r + h_c)] / [\lambda_{cl} R_o + R_o R (h_r + h_c) \ln (R/R_o)]. \quad (\text{equation 4})$$

The values for h are finally integrated over the various cylinders to produce the total heat transfer coefficient ht .

The conversion of ht to the insulation in clo units is then achieved with:

$$I_t = 1/0.155 \text{ ht} \quad (\text{clo}). \quad (\text{equation 5})$$

This equation gives the total insulation of clothing plus adjacent air. In experimental studies this is often the variable that is measured, although interest is focused on the clothing itself. The definition of clothing insulation per se is:

$$I_{cl} = I_t - (I_a/f_{cl}) \quad (\text{clo}), \quad (\text{equation 6})$$

where I_{cl} is intrinsic clothing insulation (clo), f_{cl} is a surface factor (no dimension) equal to the outer surface area of the clothing over the skin surface area.

This heat transfer model was implemented in a computer program (CLOMAN2 V1.0) that allows input for clothing conductivity, the air heat transfer coefficient, and the thickness of clothing on various body parts relative to trunk insulation thickness. In figure

1 the relationship between I_{cl} and clothing thickness is shown for various distributions of insulation over the body.

Insulation is usually unevenly distributed over the body for reasons of mobility and comfort. An estimated distribution for cold weather clothing is that the thickness relative to that for the trunk is 0.7 for the arms, 0.5 for the legs, 0.3 for the feet and head, and 0.2 for the hands. If a person were to have a flat surface, the insulation would increase linearly with the thickness of the clothing and conform to the line marked "flat" in figure 1. Due to the cylindrical shape of body parts some insulation is lost, however, since the outer surface increases and can lose more heat. The result is shown by the curve "full" in the figure. Apparently the loss of insulation due to curvature is limited. Exposed skin decreases the total insulation dramatically, despite the limited skin areas involved (7 % for head, 5 % for hands, and 7 % for feet). This effect is even stronger when the air convection is high, due to wind (lowest curve). For example, the intrinsic insulation drops by 50 % when h_c increases from $5 \text{ W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$ ($0.4 \text{ m} \cdot \text{s}^{-1}$, light air) to $25 \text{ W} \cdot \text{m}^{-2} \cdot ^\circ\text{C}^{-1}$ ($10 \text{ m} \cdot \text{s}^{-1}$, fresh breeze).

From these considerations three important observations emerge. First, although the effect of curvature may considerably affect local insulation, particularly for the extremities, it is of minor importance for the intrinsic insulation of the ensemble. Second, intrinsic insulation is not a specific clothing constant, but depends instead on air convection. Apparently the concept of intrinsic insulation is meaningful only for a standard environment, for example, indoors. Using intrinsic insulation values to predict comfort or heat stress in another environment thus leads to errors. The problem is due to the exposed skin. If intrinsic insulation were redefined in terms of covered skin area, in contrast to total skin area, it would be largely, but not completely, independent of wind. Third, exposed skin

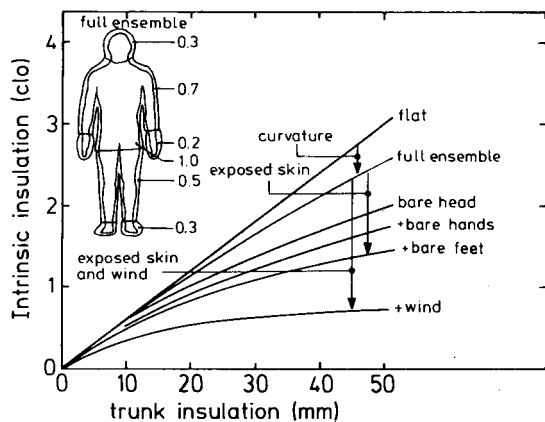


Figure 1. Intrinsic clothing insulation as a function of clothing thickness for various distributions of insulation (slightly tight-fitting clothing).

and wind together may limit the insulation of thick garments to less than 1 clo. Winter ensembles must thus have increased skin coverage. This last point has been treated in more detail later.

Figure 2 shows the total insulation (I_t) that is obtained with a certain volume of insulative material for

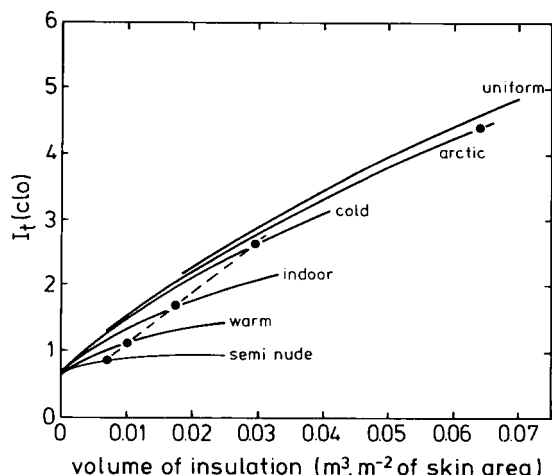


Figure 2. Total insulation (I_t) obtained with six typical distributions of insulation under still air conditions as a function of the volume of the insulative material. The broken line represents the insulation of common clothing.

Table 1. Typical thickness of insulation on the extremities of the body for typical clothing fitting six different environmental conditions; trunk insulation has been used as reference.

	Legs	Arms	Hands	Feet	Head
Body seminude	0.0	0.0	0.0	0.0	0.0
Warm environment	0.1	0.1	0.0	0.2	0.0
Indoor environment	0.5	0.7	0.0	0.3	0.0
Cold environment	0.5	0.7	0.2	0.3	0.3
Arctic environment	0.7	1.0	0.5	0.5	0.5
Uniform thickness	1.0	1.0	1.0	1.0	1.0

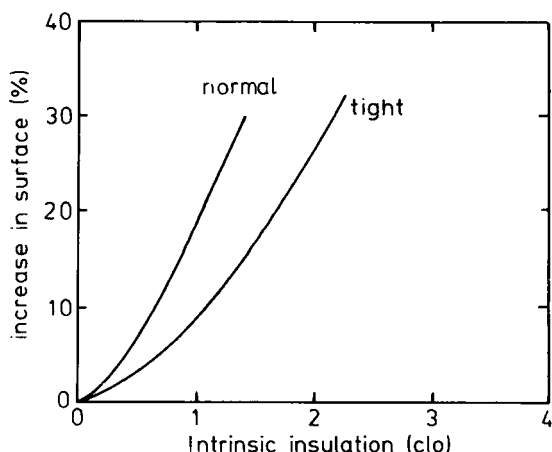


Figure 3. Calculated surface ratio f_{cl} as a function of intrinsic insulation for normal and tight fitting garments.

seminude humans, for typical ensembles for warm, indoor, cold and arctic environments, and for a uniform distribution, and table 1 presents the typical distribution on the extremities with the trunk insulation as reference. For the same amount of insulative material the highest insulation is obtained with a uniform distribution over the body. Arctic ensembles are definitely more uniform than warm weather clothing, with the head, hands, arms, and legs bare. When the approximate insulation values for the different ensembles are plotted (figure 2), the total insulation of actual clothing is linearly related to the volume of insulation material, except for very thick clothing, whose efficiency is already close to optimum. Since there is a limit to the bulk of clothing that can be tolerated, the total insulation will hardly ever exceed the value of 5 clo.

Another point of interest is the increase in the outer surface area of clothing. When the outer surface is much larger than the area of the skin, the effective insulation of the air decreases with the ratio of the two areas (introduced in equation 6) as follows:

$$f_{cl} = \text{clothing surface area}/A_D \quad (\text{no dimension}), \quad (\text{equation 7})$$

where A_D is the DuBois & DuBois (5) body surface area (m^2). The air insulation is then determined as (similar to equation 3):

$$I'_a = I_a/f_{cl} = 1/[f_{cl} \cdot 0.155 \cdot (\text{hr} + \text{hc})]. \quad (\text{equation 8})$$

The effect of clothing thickness on total insulation is thus counteracted by a loss of air insulation, in addition to the decreased efficiency due to curvature (figure 1). In figure 3 the calculated f_{cl} is shown as a function of the intrinsic insulation, both for normal-fitting ($\lambda_{cl}=0.080 \text{ W} \cdot \text{m}^{-1} \cdot ^\circ\text{C}^{-1}$) and for tight-fitting ($\lambda_{cl}=0.040 \text{ W} \cdot \text{m}^{-1} \cdot ^\circ\text{C}^{-1}$) garments. The increase in the f_{cl} factor is more or less proportional to I_{cl} :

$$f_{cl} = 1 + c \cdot I_{cl} \quad (\text{no dimension}), \quad (\text{equation 9})$$

the coefficient varying from 0.08 for light, tightly fitting garments to 0.25 for warm, normally fitting garments. It will be shown later that the latter value is more realistic than the former. Consequently the higher value for λ_{cl} is more likely than the value of 0.040. This conclusion supports the already mentioned rejection of the 4-clo-per-inch rule of thumb.

Measurement of garment characteristics

Most clothing insulation measurements are done on thermal manikins. The first available manikins were those of the United States Army in 1942. Some of them are still in use, but many new devices have been designed, such as the Hohenstein equipment and the TORE manikins from Scandinavia. The first manikins were static, but the more recent ones can be motor-driven to imitate walking or cycling.

Sweating is a technological problem. The old manikins were covered with a wet cloth underneath the clothing to evoke a vapor flow, but the cloth tends to dry out before the clothing is conditioned. This was an obstruction to reliable measurement. Fully wetting a manikin is possible, but keeping the surface at a controlled wetness is difficult. A recent sweating manikin is the Finnish COPPELIA, but it is still only a prototype. Due to these problems manikins are mainly being used for heat flow measurements. The vapor resistance characteristic of clothing is usually extrapolated from flat plate results.

Tables of insulation values have been published (1, 6—9) for a wide variety of clothing items and ensembles. In order to find the insulation of a specific ensemble that is not included in the list, one looks up the items in the ensemble in the table and uses a regression equation to find the ensemble insulation:

$$I_{cl} = a \sum I_{cli} + b \quad (\text{clo}), \quad (\text{equation 10})$$

where I_{cli} refers to the separate items. The values for the constants a and b vary between authors. They are listed in table 2. Applying the various formulas to clothing ensembles with $\sum I_{cli} = 0.5$ and 1.5 clo, respectively, shows that Goldman's prediction is rather low. The other predictions agree within 15 % for the light ensembles and within 7 % for the heavier ensembles with the average formula:

$$I_{cl} = 0.75 \sum I_{cli} + 0.09 \quad (\text{clo}). \quad (\text{equation 11})$$

In view of the theoretical considerations presented in the section "From Fabric to Clothing," regression equation 10 is peculiar. The weight factors of the separate clothing items should not be constant, but should instead depend on the other items of the ensemble and, in particular, on the uncovered skin area. The fact that, with equation 10, with uniform weights, the correlation coefficient of 0.97 is obtained (1) must be due to the fact that the heavier ensembles also have a more uniform distribution of insulation, as demonstrated in figure 2. A close look at the data of McCullough et al shows indeed that ensembles with insulation predominantly on the trunk have lower insulation values than ensembles with a better distribution.

For the calculation of I_{cl} , not only I_{cli} must be available, but also the surface factor f_{cl} . (See equation 6.) In table 3 the literature values for f_{cl} have been compiled. When the deviating value of Fanger (14) is omitted, the various sources agree within 5 % of the value obtained with the following equation:

$$f_{cl} = 1 + 0.29 \cdot I_{cl} \quad (\text{no dimension}). \quad (\text{equation 12})$$

This value compares well with the estimated value of $1 + 0.25 \cdot I_{cl}$ for normal clothing in figure 3. It should be noted that the latter estimate is based on the assumption that the clothing surface is a perfect cylinder, whereas real clothing shows folds that increase the actual surface. Mekjavic & Sullivan (16) have

reported that the representation of clothing by various cylindrical elements provides a fair estimate of the actual surface. When the clothing is extremely folded, a quick estimate of the actual surface may be made with planimetric measurement of the clothing that forms the outer surface when overlaps and uncovered area are taken into account.

The use of clothing tables is not unambiguous. McCullough et al (1) showed that even trained textile students experience difficulties in identifying clothing items from those listed in the tables, the result being a standard deviation of 23 % in the intrinsic insulation. It is thus not the inaccuracy of the table, but the way the table is used that introduces error. Several other methods for determining clothing insulation have been tried, including regression on the weight, thickness, and body coverage of the clothing. The most accurate of these are the following equations given by McCullough et al (1):

$$I_{cl} = 0.0079 \cdot \text{BSAC} + 0.00131 \cdot \text{th} \cdot \text{BSAC} - 0.0745 \quad (\text{clo}) \quad (\text{equation 13})$$

for separate clothing items, and

$$I_{cl} = 0.676 \sum I_{cli} + 0.117 \quad (\text{clo}) \quad (\text{equation 14})$$

for the ensemble, where BSAC is body surface area covered (%), and th is thickness (mm) of the clothing items according to the American Society for Testing and Materials (17) at a pressure of 69 Pa. This method has a standard deviation of 0.09 clo. Slightly less

Table 2. Values for the constants a and b in equation 10 according to data compiled by Havenith (13).

Author	Constant	
	a	b
Sprague & Munson (9)		
Men	0.727	0.113
Women	0.770	0.050
ASHRAE (10)	0.820	0.000
Olesen & Nielsen (11)	0.730	0.170
Goldman (12)	0.690	0.000
McCullough et al (1)	0.676	0.117

Table 3. Values for the constant c in equation 9 according to data compiled by Havenith (13).

Author	Constant c
Fanger (14)	0.15
Seppanen et al (8)	0.25
McCullough & Jones (15)	0.34
McCullough & Jones (15) using data from Sprague & Munson (9)	0.29
Olesen & Nielsen (11)	0.26
McCullough et al (1)	0.31

accurate (standard deviation 0.12 clo), but less laborious is the equation (1):

$$I_{cl} = 0.255 \cdot W - 0.00874 \cdot BSAC0 - 0.00510 \cdot BSAC1 + 0.919 \text{ (clo)}, \quad (\text{equation 15})$$

where W is weight (kg) without shoes, $BSAC0$ is the uncovered body area (%), $BSAC1$ is the body area covered with one layer (%).

A basically different technique to measure the thermal characteristics of clothing is partitional calorimetry, developed in the laboratory of the JB Pierce Foundation in the late 1930s. Human subjects are used as living calorimeters in this technique with the aim of

measuring the components of the heat balance equation:

$$M = W_{ext} + Dry + Evap + Resp + Store \quad (W), \quad (\text{equation 16})$$

where M is metabolic heat production, W_{ext} is the external work performed, Dry is the dry heat loss due to conduction, convection and radiation, $Evap$ is the evaporative heat loss, $Resp$ is the respiratory dry and evaporative heat loss, and $Store$ is the rate of heat storage in the subject. All the terms in equation 16 are measured or estimated, except for Dry , which can thus be calculated from the heat balance. The heat transfer coefficient ht and the vapor resistance, expressed as the air equivalent d , are then obtained from:

$$ht = Dry / [A_D (T_{sk} - T_a)] \quad (W \cdot m^{-2} \cdot ^\circ C^{-1}) \quad (\text{equation 17})$$

and

$$d = [(A_D \cdot He \cdot 1000 \cdot ID) / Evap] (C_{sk} - C_a) \quad (\text{mm}), \quad (\text{equation 18})$$

where A_D is the DuBois body surface area (m^2), T_{sk} is the mean skin temperature, T_a is the air temperature, He is the heat of evaporation (J/g), ID is the diffusion coefficient ($m^{-2} \cdot s^{-1}$), C_{sk} is the mean skin vapor concentration ($g \cdot m^{-3}$), C_a is the air vapor concentration ($g \cdot m^{-3}$), ht is the heat transfer coefficient ($W \cdot m^{-2} \cdot ^\circ C^{-1}$), and d is the air equivalent (mm) (ie, the thickness of a still air layer that would have the same vapor resistance as the sample).

Thus during one experimental session both the heat and the vapor characteristic of the clothing can be obtained. In reality there is variation due to differences between subjects and experimental error. A good experimental design and corresponding statistical analysis is thus necessary. The heat balance technique demands more experimental skills and more effort than the manikin technique, but the results are of a higher order. The clothing parameters are obtained during realistic physiological conditions, there are few restrictions to the kind of activity of the subjects, the actual thermal strain can be observed, and the results can be interpreted in light of interindividual variability.

Olesen & Nielsen (11) concluded that partitional calorimetry is too inaccurate and too laborious to compete with manikin measurements. Although their conclusion is too bold, there is some truth in it. Lotens et al (18) modified the technique to obtain a higher accuracy at the expense of realism of the physiological condition. To increase Dry , and hence its accuracy, $Evap$ is suppressed by wrapping the subject in plastic (figure 4). Thus ht can be determined with a relatively small error. The measurement of vapor permeation is not done by sweat diffusion, but by the diffusion of a tracer gas that is not absorbed in the clothing. This measurement can then be typically carried out in 5 min, instead of the at least 1 h needed with



Figure 4. A subject wrapped in plastic for the modified heat balance technique. The clothing still has to be donned.

actual sweat. This tracer gas technique has been developed and evaluated by Lotens & Havenith (19).

The question has been raised of whether insulation measured on a manikin and on subjects is identical. At first sight this seems to be a simple question, but there are many complications involved. The sweat production of humans causes a vapor flow which interacts with the heat flow in a complicated way. There are experimental traps that may lead to errors. Furthermore the fit of the clothing should be the same for the manikin and the subjects, and their posture should also be the same. In addition the skin temperature distribution should be the same, the subjects should be bald, and they should not breathe and move their chest. Thus, if experimenters succeed in making these conditions identical for manikins and for subjects, they would have a fair comparison, but there would hardly be a reason for different insulation values being obtained. In other words, it is not so much that manikin values are different but that they only represent one aspect of a complicated matter. More interesting is the question of whether satisfactory corrections can be given for manikin values to predict realistic heat transfer for humans. The aforementioned techniques provide useful tools in the investigation of such corrections. In the next sections the various factors involved are considered in detail.

Posture and fit

Since enclosed air layers constitute a considerable part of total insulation, it is anticipated that a change in the fit of clothing or in posture affects the insulation. During sitting the air will be driven out the thigh, buttock, and back areas, and insulation will probably decrease in comparison with insulation during standing, whereas the effective radiant surface decreases. The insulation of the adjacent air may thus increase. The chair may add insulation, but in tests usually netting chairs or stools are used that provide negligible insulation.

There are few studies to quantify the effect of fit. Lotens et al (18) did a study using repeated heat balance measurements on a lean and an obese subject with garments of a single size. The garments were thus tightly fitting for the obese subject (1.85 m, 88 kg) and loosely fitting for the lean subject (1.78 m, 61 kg). Measuring the temperature inbetween the layers gave the insulation values for the adjacent air layer, the protective outer garment, the air gap between the outer garment and the fatigues, and the fatigues. Due to the dimensions of the temperature sensors, it was inevitable that some air insulation was incorporated into the calculated insulation of the clothing layers, at the expense of the calculated insulation of the air layers. Table 4 shows that, during sitting, the total insulation was not different between the tight and loose fits, but, during standing, it was distinctly greater with the loose fit. The difference was primarily due to the fatigues

that, for the lean subject, tended to fill the larger space between the body and the outer garment. A comparison of the sitting and standing posture shows a striking difference in total insulation, to which all layers except the adjacent air contributed.

With typical indoor and work ensembles the effect of posture is not so strong, but it is still clearly present. Nielsen et al (20) measured clothing insulation on men and women and concluded that I_{cl} decreased 10–20 % during sitting, while I_a increased 10–20 %. Olesen et al (7) found similar values with a movable manikin, be it that the increase in I_a was only 5 %. In figure 5 the total insulation values during sitting have been compiled as a function of insulation during standing. The net effect of changes in clothing and air insulation is rather small. For light clothing there is an increase of 10 % during sitting, but with heavy clothing there is a decrease. In particular garments with large air chambers may show a stronger decrease.

Wind and body motion

Both wind and body motion may affect insulation through the induction of air motion. When outside air

Table 4. Insulation for various layers of an ensemble for protection against chemical exposure under different conditions of fit and posture, according to data from Lotens et al (18). The area factor has been included in the insulation values.

Fit	Adjacent air (clo)	Outer layer (clo)	Enclosed air (clo)	Fatigues (clo)	Total (clo)
Loose					
Sitting posture	0.55	0.41	0.21	0.43	1.60
Standing posture	0.57	0.70	0.57	0.95	2.79
Tight					
Sitting posture	0.55	0.48	0.30	0.30	1.63
Standing posture	0.42	0.72	0.49	0.50	2.13

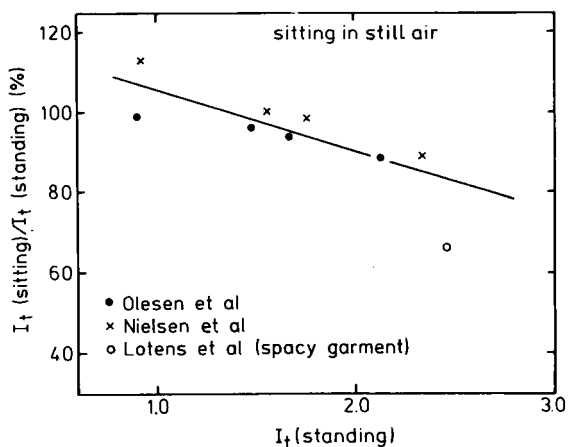


Figure 5. Total insulation during sitting, relative to standing, for various ensembles according to Olesen et al (7), Nielsen et al (20), and Lotens et al (18).

penetrates the clothing, either via closures or through the material, the effect is called ventilation. When there is no air exchange, but rather an increased circulation underneath the clothing or at the surface of the clothing, it is called convection. Usually ventilation and convection will be concomitant.

Vokac et al (21) were among the first to assess "below ventilation," ie, circulation underneath a garment due to rhythmic body motion during walking. This convection may decrease the insulation, but the effect is difficult to discern from outside convection. In reality the only activities that have been used to measure motion effect are those that are easily controlled in an experimental situation, ie, walking (4–5 km/h) and cycling (about 40 revolutions/min). Nielsen et al (20), who performed a direct comparison of the two activities, concluded that both I_{cl} and I_a are higher during cycling than during walking, but lower than during standing. This statement applies to conditions without wind, and the result is understandable from the fact that, during cycling, the arms and back are more static than during walking. In addition posture may have an effect, eliminating ventilation of upper body parts during cycling.

Figure 6 shows the findings of various researchers for walking and cycling. The figure proves that ventilation and convection decrease the insulation of a wide range of clothing to an equal degree, and, moreover, as for seminude subjects ($I \approx 1.0$ during standing). There may be a slight increase in the loss of insulation as clothing thickness increases, but the data are not conclusive. For many clothing ensembles the results

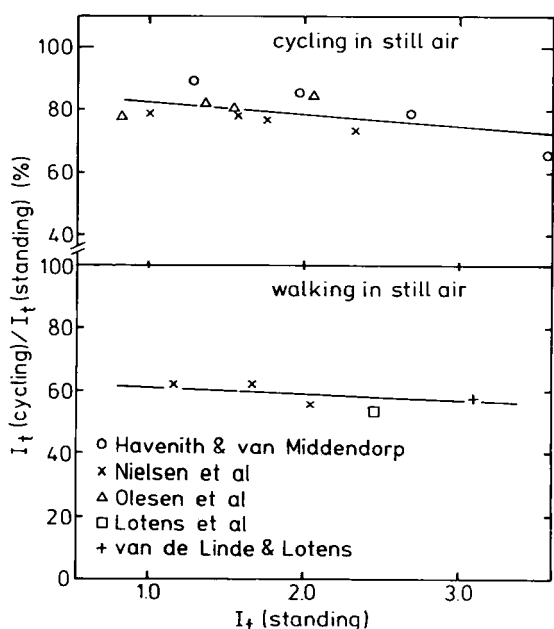


Figure 6. Total insulation during cycling and walking (lower part of figure), relative to standing, for various ensembles, according to Havenith & Van Middendorp (22), Nielsen et al (20), Olesen et al (7), Lotens et al (18), and van de Linde & Lotens (23).

could be summarized by the statement that walking decreases the total insulation by 40 % and cycling by 20 %. On the recognition that the difference between the two activities is the motion of the upper body, this statement could also be formulated as: the motion of the upper part of the body and the motion of the lower part of the body each cause a 20 % loss of insulation.

In wind the adjacent air layer is thinner and, due to the pressure, air may penetrate into the clothing. Fonseca & Breckenridge (24) used a cylindrical calorimeter to show that the insulation is predominantly lost at the windward side and that there is another, much lower peak on the lee side. The penetrating air enters the first clothing layer on the windward side, flows around the cylinder in the air gap between the layers, and leaves on the lee side. When the flow in the gap is hampered by fiber material, the second clothing layer is also penetrated on the windward side, and the net result is that the addition of fiber material actually decreases the total insulation. The data of Fonseca & Breckenridge for the total heat transfer coefficient show a linear relationship with $\sqrt{V}$ (V is wind speed), with a slope dependent on the air permeability of the windbreak layer and the air gap underneath:

$$h = d\sqrt{V} + e \quad (\text{m}^2 \cdot ^\circ\text{C} \cdot \text{W}^{-1}). \quad (\text{equation 19})$$

On theoretical grounds Stuart & Denby (25) predicted a $\sqrt{V}$ dependency as well. Fonseca & Breckenridge (24) showed with their calorimeter that the insulation drops with the opening of vents and the drop is larger when the air gap between the first two clothing layers is increased. Lotens & Havenith (19) found the same phenomenon during direct measurements of ventilation on humans when they increased the air gap by means of a harness of foam strips.

Surprisingly, there are only a few studies that evaluate clothing insulation for standing humans as a function of air motion. The effect of air motion on the insulation of the adjacent air layer is well known from both physiological measurements [$h_c = 8.3 \sqrt{V}$ (from reference 26)] and physical measurements [wind-chill chart (27)], but the effect on I_{cl} has not been as well investigated. In figure 7 the data have been calculated with equation 19 as rewritten for this application:

$$I_t = I_{t0.3} [(f\sqrt{0.3} + 1)/(f\sqrt{V} + 1)] \quad (\text{clo}), \quad (\text{equation 20})$$

where $I_{t0.3}$ is the insulation at $V = 0.3 \text{ m} \cdot \text{s}^{-1}$. (This value was used for reference because, in most studies, there is some light air motion and natural convection); f is equal to d/e in equation 19 and has the value 1.3 for light clothing, 0.8 for medium heavy clothing, and 0.4 for heavy clothing.

It should be noted that heavy clothing will usually be more airtight than light clothing. No distinction has been made between air permeability and clothing thickness. Although there is some variance in figure 7, probably due to the difference in the windbreaking property of the clothing, there is a general decline in insu-

lation with increasing wind speed, the decline being greater for light clothing than for heavy clothing.

Givoni & Goldman (29) published the following prediction equation:

$$I_t = I_{t,1.0} V^{-p} \quad (\text{clo}), \quad (\text{equation 21})$$

where $I_{t,1.0}$ is defined at $1 \text{ m} \cdot \text{s}^{-1}$. This equation was introduced to explain discrepancies between measured and predicted heat stress for low air motion and is fitted basically at 0.5 and $5 \text{ m} \cdot \text{s}^{-1}$ (30). The pumping coefficient p has the value of 0.25 for light clothing, 0.2 for medium heavy clothing, and 0.15 for heavy clothing.

Equations 20 and 21 provide nearly the same figures, except for high wind speed, for which equation 21 predicts insulations that are too high since there is an increasing discrepancy between light clothing and pure air.

The combined effect of body motion and wind is not a summation of the two, since there is an interaction. Wind induced by body motion should, true enough, be added to external wind, but the effect of this total wind speed is less than proportional, as figure 7 proves. Thus, in wind, the effect of body motion is reduced. Givoni & Goldman (29) expanded equation 21 to take both wind and motion of walking into account:

$$I_t = I_{t,1.0} V_{\text{eff}}^{-p} \quad (\text{clo}), \quad (\text{equation 22})$$

where V_{eff} is the effective wind speed,

$$V_{\text{eff}} = V + 0.004 (M - 105) \quad (\text{m} \cdot \text{s}^{-1}), \quad (\text{equation 23})$$

and M is the metabolic rate. For walking in still air, with an approximate metabolic rate of 360 W , V_{eff} amounts to slightly more than $1 \text{ m} \cdot \text{s}^{-1}$, which is a value too low to explain the 40% loss of insulation found in figure 6, ie, $6 \text{ m} \cdot \text{s}^{-1}$ for heavy garments and $2 \text{ m} \cdot \text{s}^{-1}$ for light clothing would be more accurate according to figure 7. The idea behind equation 23 is probably correct, however. According to this idea, when the effect of wind and walking on the relative insulation is determined at a wind speed of $4 \text{ m} \cdot \text{s}^{-1}$ for the two available references, 55% is predicted for heavy clothing rather than the measured value of 52% (23) ($10 \text{ m} \cdot \text{s}^{-1}$ effective wind speed), and for air only at $1.1 \text{ m} \cdot \text{s}^{-1}$ 51% is predicted ($3.1 \text{ m} \cdot \text{s}^{-1}$ effective wind speed) rather than the measured 47% (20). Thus figure 7 could be a valuable tool for the estimation of insulation.

Lotens & Havenith (19) applied the trace gas technique to measure the ventilation of windproof rainwear and thus obtained the ventilation through the closures. The results shown in figure 8 prove that at least for the ventilation part of the heat loss, the equivalent wind velocity of walking amounts to more than $2 \text{ m} \cdot \text{s}^{-1}$ for the jacket and more than $6 \text{ m} \cdot \text{s}^{-1}$ for the trousers. These values are not inconsistent with those deduced from figure 7.

Effect of ventilation on vapor permeation

It is not an unusual practice to determine the relation between heat and vapor permeation on a flat plate and extrapolate this value (eg, i_m or equivalent) to the complete garment worn by subjects. From a theoretical point of view this procedure is not correct. The heat transfer is given by:

$$\text{Dry} = (\text{hcd} + \text{hr}) A_D (T_{\text{sk}} - T_a) \quad (\text{W} \cdot \text{m}^{-2}), \quad (\text{equation 24})$$

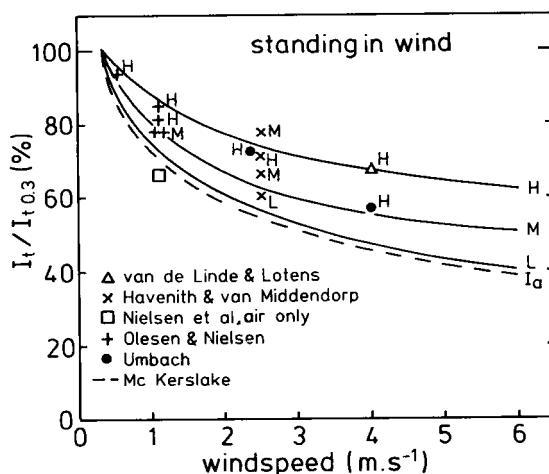


Figure 7. Total insulation during standing in the wind, relative to an air velocity of $0.3 \text{ m} \cdot \text{s}^{-1}$, according to van de Linde & Lotens (23); Havenith & Van Middendorp (22); Nielsen et al (20), air only; Olesen & Nielsen (11); and Umbach (28). The solid lines are predicted with equation 20 in the text, and the broken line represents the measurements (air only) of McKerslake (26). (H = heavy clothing, M = medium weight clothing, L = light clothing).

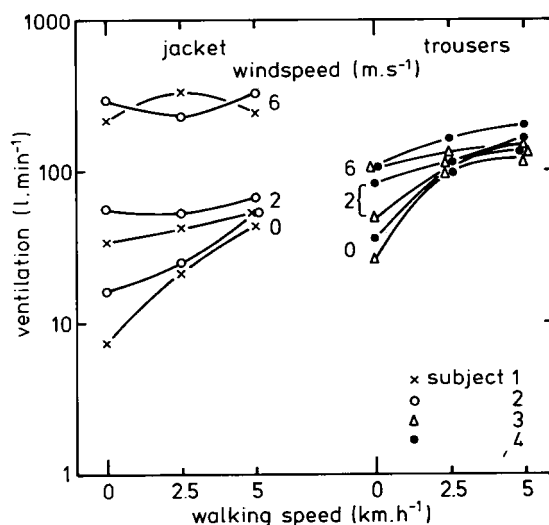


Figure 8. Ventilation of rainwear as a function of walking speed and wind speed according to Lotens & Havenith (19).

where h_{cd} and h_r are the conductive and radiative components of the clothing plus air heat transfer coefficient, respectively; h_{cd} is almost invariably the heat transfer coefficient of still air, amounting to $0.026/th$ (th being the thickness of clothing + air) since fiber conductivity is only important in cases with extremely dense fabrics. The latent heat transfer is represented by:

$$Evap = L \cdot h_{cd} \cdot A_D \cdot (C_{sk} - C_a) \quad (W \cdot m^{-2}). \quad (\text{equation 25})$$

When ventilation is induced, there is convective transfer in addition to conduction, and equations 24 and 25 must be modified:

$$Dry = (h_{cd} + h_{cv} + h_r) A_D (T_{sk} - T_a) \quad (\text{equation 26})$$

and

$$Evap = L (h_{cd} + h_{cv}) A_D (C_{sk} - C_a), \quad (\text{equation 27})$$

where h_{cv} is the convective heat transfer coefficient. (It is neglected that the value of L is not exactly the same for h_{cd} and h_{cv} .) The convection makes $Evap$ obviously change faster than Dry , and there is no simple proportionality. In fact, equations 26 and 27 provide a means for estimating the component h_r . In the experiments of Lotens et al (18) on standing subjects, the dry heat transfer coefficient was changed by a factor of 1.85 by the introduction of wind with a velocity of $3 \text{ m} \cdot \text{s}^{-1}$, whereas the latent heat transfer coefficient was changed by a factor of 3.75:

$$(h_{cd} + h_r + h_{cv}) / (h_{cd} + h_r) = 1.85 \quad (\text{equation 28})$$

and

$$(h_{cd} + h_{cv}) / h_{cd} = 3.75. \quad (\text{equation 29})$$

Substitution of equation 27 into equation 28 immediately reveals

$$h_r = 2.2 \cdot h_{cd}.$$

Apparently, in the type of clothing used, the radiant heat transfer dominates when a person stands in still air, but it is challenged by the convection of the wind ($h_{cv} = 2.75 \cdot h_{cd}$ according to equation 29). The average conductivity of the clothing is then:

$$\begin{aligned} th (h_r + h_{cd}) &= 3.2 \cdot th \cdot h_{cd} \\ &= 3.2 \cdot 0.026 \\ &= 0.084 \text{ W} \cdot \text{m}^{-1} \cdot ^\circ\text{C}^{-1}, \end{aligned}$$

the result supporting the formerly mentioned estimate of $0.080 \text{ W} \cdot \text{m}^{-1} \cdot ^\circ\text{C}^{-1}$ for normal clothing ensembles.

Concluding remarks

A simple model of a human built from various cylinders and clothed in a homogeneous layer of insulation material shows that the rule of thumb that clothing provides 4 clo of insulation per inch of thickness is an overestimation and that the concept of in-

trinsic insulation is not independent of the environmental conditions, in contrast to the aim. The distribution of insulation over the body and, in particular, exposed skin has a strong influence on basic insulation. The insulation table values are therefore only valid for indoor environments.

Various tables of clothing insulation do agree closely, but their use is complicated by the problems of identifying clothing items. Regression on the weight, surface coverage, and thickness of the clothing may provide greater accuracy.

The obtained ensemble insulation values are basically valid for standing humans only, but their application may be extended to real tasks by the use of correction factors for posture, fit, motion, and wind. The effect of fit can be summarized by the statement that the space under the outer garment is either filled by body tissue (tight fit) or by enclosed air (loose fit). Sitting shows a slight increase in insulation for light clothing and a slight decrease for heavy clothing in comparison to standing. Cycling causes a 20 % and walking a 40 % loss of insulation, almost regardless of the clothing. The effect of wind is linearly related to $\sqrt{V}$, with a stronger effect on light than on heavy clothing. In particular the effects of motion and wind are so strong that for many outdoor conditions the insulation is less than half the table value. Vapor transfer through clothing is more sensitive to wind than heat transfer is.

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Wind-chill equations predicting whole-body heat loss for a range of typical civilian outdoor clothing ensembles

by David P Wyon, PhD¹

WYON DP. Wind-chill equations predicting whole-body heat loss for a range of typical civilian outdoor clothing ensembles. *Scand J Work Environ Health* 1989;15(suppl 1):76–83. A thermal manikin with constant skin temperature and a wind-chill tunnel with constant air temperatures and wind speeds were used to measure whole-body heat loss for seven ensembles chosen to represent the full range of civilian outdoor clothing in use for everyday, nonsporting wear. Equations fitting the data with correlation coefficients exceeding 0.99 were derived for each ensemble, and diagrams were produced with these equations to interpolate and extend the range of conditions. The conditions studied were those resulting in total heat loss from 50 to 250 W · m⁻², so very little extrapolation was required. The wind-chill equivalent temperature (with reference to 2 m · s⁻¹), based on the average value for all seven ensembles, showed good agreement on this measure. The values predicted on the basis of whole-body heat loss through clothing were shown to be much lower than those predicted from the Siple wind-chill index for unprotected skin.

Key terms: clo, index thermal insulation, temperature, thermal manikin, wind speed.

Buildings can affect the microclimate in their immediate vicinity in a variety of ways. For example surface materials, textiles, and color affect radiation temperatures considerably if wind speeds are low; and building shapes, juxtapositions and heights, and their ancillary walls, fences and vegetation all affect local wind speeds. The resulting microclimate determines the heat balance of people wearing a wide range of clothing while engaged in a wide variety of activities.

As far as possible, building design should take account of these thermal requirements. For instance, the season for sitting outside or for using a playground or for going to the car and running local errands in indoor clothing may possibly be extended by several months. Waiting for a bus or to cross a road may be made less of an ordeal by the proper design of the microclimate.

However, necessary modifications to a built environment may be prohibitively expensive once a building complex has been completed, and it is therefore desirable to be able not only to predict the expected microclimate, in physical terms, but also its resulting effect on human heat balance and human activities. The physical effects on the microclimate may be studied by means of scale models in an appropriate wind tunnel and verified by means of field measurements (1, 2), but the effects on human heat balance have hitherto been very difficult to predict with any accuracy.

The conventional wind-chill index, derived by Siple & Passel (3) from studies of the rate of cooling of cans of water, is appropriate for exposed skin, but not for

the clothed body unless the outer layer of clothing is completely windproof and all extremities are equally well protected. It may be used for predicting the risk of frostbite on the face or unprotected hands and for military or survival purposes when clothing may be assumed to approximate the aforementioned conditions, but it is not useful for the civilian clothing, low wind speeds, and relatively mild temperatures of interest in the present discussion. Heat balance equations which take account of clothing assume that clothing insulation values are unaffected by wind and assume the characteristic square-root dependence of heat loss on air velocity that is appropriate for impervious cylinders. To the extent that civilian clothing is not impervious to wind and does not protect all parts of the body equally, these assumptions will be wrong and will lead to an underestimate of the effects of wind and of the potential benefits of microclimate modification.

The present study was undertaken to derive empirical equations predicting the combined effects of wind and temperature on total heat loss for a range of civilian clothing in everyday use, from shirt-sleeves to down-jackets. A wind-chill chamber was constructed for the purpose, and the measurements of whole-body heat loss were made with the 16-section thermal manikin SIBMAN, a full-size model of a standing man. Air-temperature and wind-speed combinations giving whole-body heat loss rates from 50 to 250 W · m⁻² (resting to heavy work) were used for each clothing ensemble. It appears to be the first time such measurements have been made.

Methods

Wind-chill tunnel

A well-insulated space, normally cooled to –20°C for heatflow studies of prototype window, outer wall and

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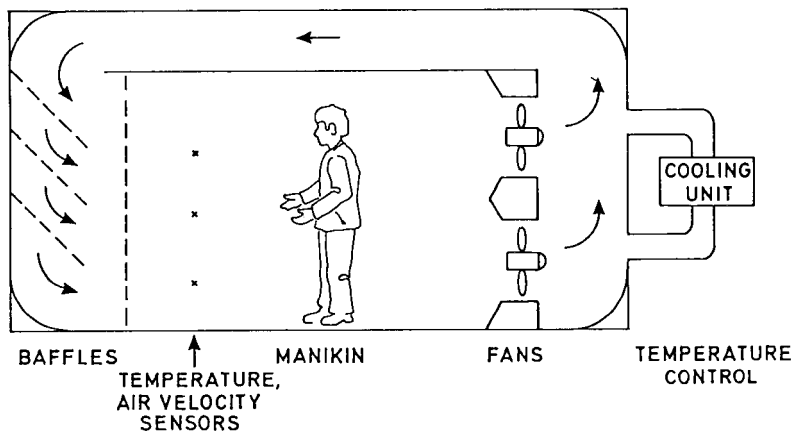


Figure 1. Wind-chill tunnel built for the experiment.

door constructions, was available. The floor was 6×1.20 m, the height 2.40 m. Two large frequency-controlled fans were installed as shown in figure 1. They drew air down the “tunnel” and returned it above a false ceiling at a height of 1.90 m. Baffles were installed as shown in the figure to reduce energy losses and to ensure an approximately even air speed at all heights above the floor. A variable amount of air was withdrawn from the tunnel after the fans; it was cooled and returned just downstream. The volume flow of this air was adjusted automatically by means of a proportional-integral regulator to maintain each preset air temperature, as measured upstream of the manikin. Fan speeds were set manually. The cooling system, with a maximum cooling effect of 10 kW, limited the maximum wind speed to about $4 \text{ m} \cdot \text{s}^{-1}$, as higher fan speeds led to a loss of temperature control. Wind speeds were measured upstream of the manikin with a hot-bead anemometer. As the manikin obstructed the airflow, some increase in air speed around the manikin, in excess of that taking place in the open, had to be assumed.

Thermal manikin

SIBMAN was the first thermal manikin built at the National Swedish Institute for Building Research, and it incorporated a number of disadvantages. A hollow plastic display manikin (Hindsgaul A/S) was fitted with joints at the elbow, shoulder, hip, and knee and divided into 16 sections. Heating wires with a resistance of 40Ω were distributed evenly over the inside surface of each section, the cables emerging from the back of the neck. Each section was filled with foam plastic to eliminate internal convection.

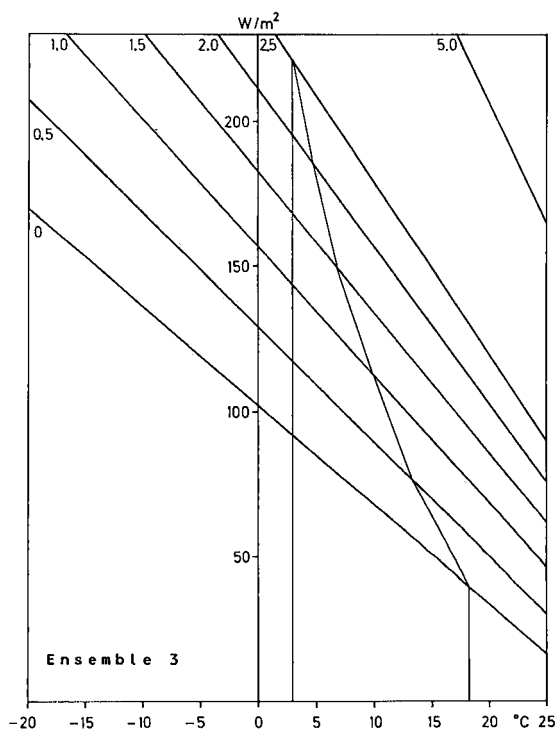
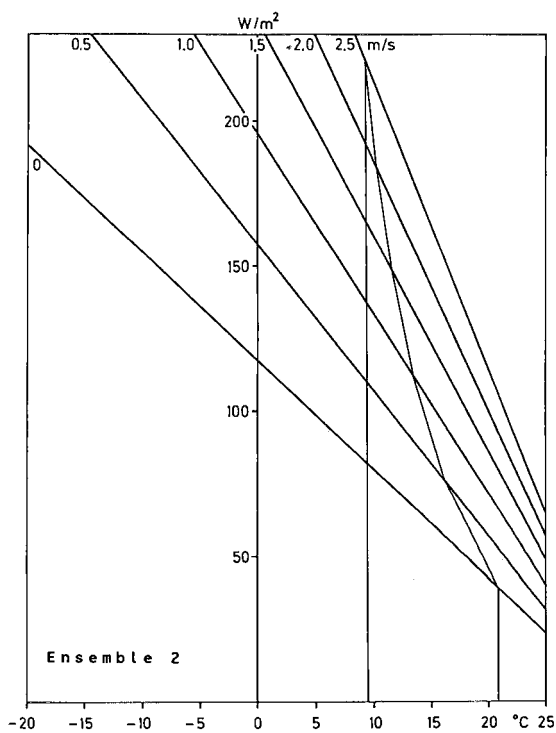
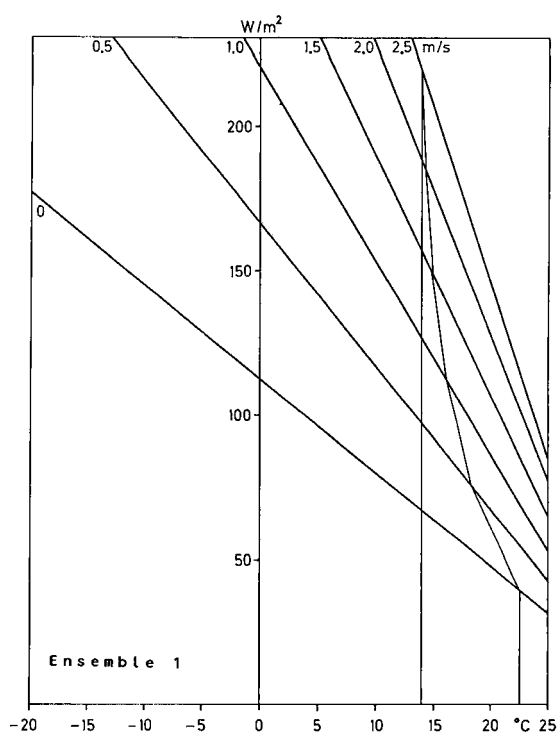
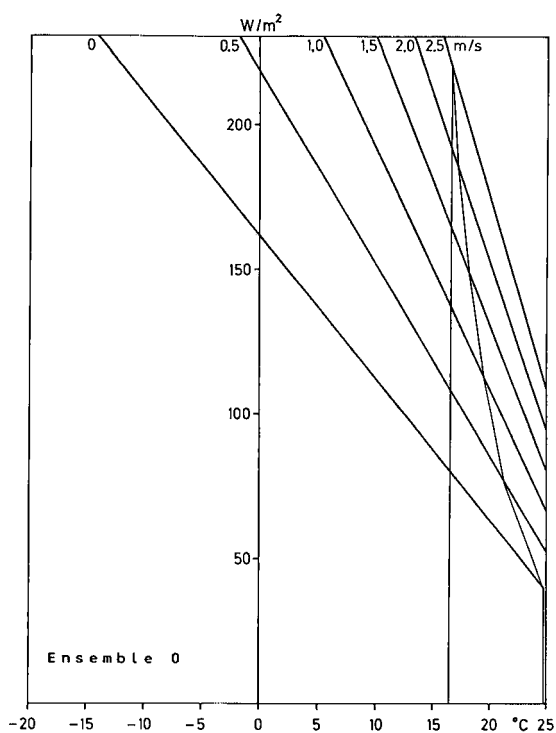
Section skin temperatures were estimated by affixing a copper-constantan foil sensor at “a representative point” determined empirically from extensive measurements of skin temperatures with the manikin heated but unclothed. The error introduced by this expedient varied, being lower the higher the clothing insulation value. Thermal manikins developed subsequently (VOLTMAN, TORE) have heating wires closer to

Table 1. Constants for each clothing ensemble in the equation $W \cdot \text{m}^{-2} = A - B \times T + C \times V - D \times V \times T$, where T is temperature ($^{\circ}\text{C}$) and V is air velocity ($\text{m} \cdot \text{s}^{-1}$).

Ensemble	A	B	C	D
0 Shirt-sleeves	161.26	4.87	113.08	3.41
1 Sweater	111.91	3.20	107.38	5.37
2 Windbreaker	118.02	3.72	76.75	2.40
3 Windbreaker, augmented ^a	101.62	3.39	54.32	0.99
4 Overcoat	86.59	2.18	118.21	4.19
5 Overcoat, augmented ^a	83.94	2.64	48.57	1.03
6 Down-jacket	75.58	2.25	57.42	2.49
Average	105.56	3.18	82.25	2.84

^a See the text for the components of the ensemble.

the surface, a metal heat-conducting layer outside the heating wires (to ensure even surface temperatures), and sensors distributed over the surface of each section. They are thus capable of simulating human heat balance in asymmetric environments, with large local variations and even shadow boundaries in direct sun. SIBMAN, though adequate for the present purpose, was found to be too sensitive to conditions at the point sensor, and it was in any case too slow in achieving equilibrium under changing conditions. The wind-chill tunnel could maintain conditions indefinitely, so time was not a limiting factor. The power supplied to each section, at a constant voltage of 55 volts direct current, was adjusted under computer control by means of pulse-length modulation, with a resolution of 1:1023 (Wessing, unpublished internal report of the National Swedish Institute for Building Research). Skin temperatures were measured by means of a conventional logger (Acurex 9) interfaced to the controlling computer (HP80). Skin temperatures could be maintained constant with an accuracy of 0.20°C ; heat flows were recorded to the nearest $1 \text{ W} \cdot \text{m}^{-2}$. The electrical measurements were made with a total accuracy of 0.2 % of full power. Section areas, measured by covering each section with masking tape, weighing the tape used to 0.01 g , and calibrating against a similarly measured cylinder of known area, were known with an accuracy of 1 %.



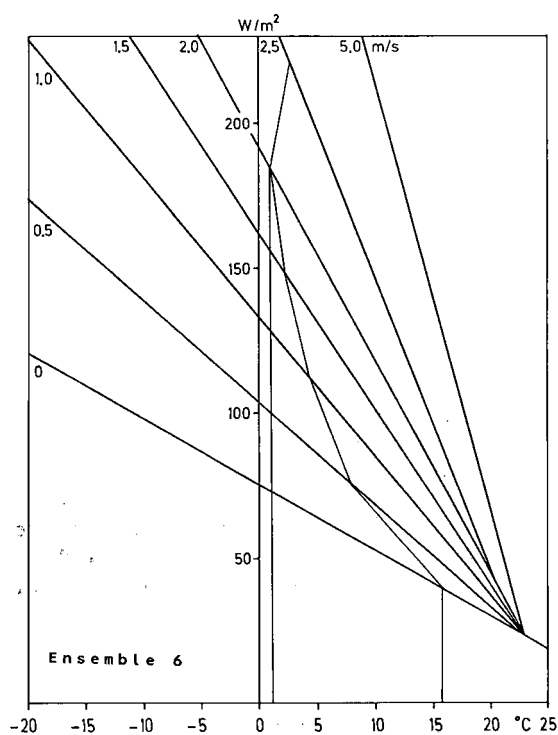
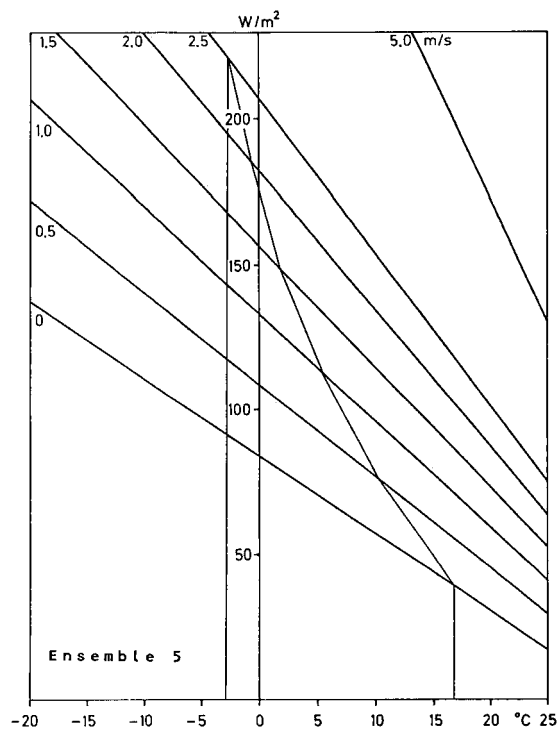
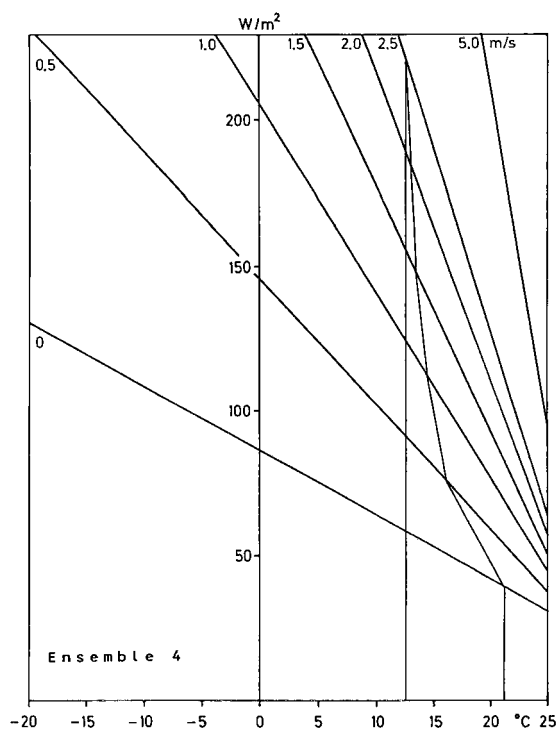


Figure 2. Predicted heat loss in watts per square meter for each ensemble. The curve in each figure is the locus of watts per square meter and meters per second for performing the activities listed in table 2. (For a description of the ensembles, see the text.)

Skin temperature distribution

Hands and feet were maintained at a temperature of 31°C, calves and lower arms at 32°C, thighs, upper arms and head at 33°C, and the trunk sections at 34°C. The area-weighted mean skin temperature was 32.8°C.

Clothing

The following seven different ensembles were measured:

Ensemble 0. Long-sleeved cotton shirt, wool trousers, cotton underpants, wool ankle socks, sturdy leather shoes with rubber soles, and nylon wig. This basic indoor ensemble was common to all of the ensembles, and only the additional items are listed in the descriptions of ensembles 1–6.

Ensemble 1. Loose-knitted sweater of thick acrylic fiber reaching to the trouser pockets, with long sleeves and a round neck.

Ensemble 2. Waist-length windbreaker with zipper, close-fitting at wrist.

Ensemble 3. Windbreaker as for ensemble 2, short leather gloves lined with cotton, knitted woolen hat covering hair and ears.

Ensemble 4. Wool overcoat extending to midthigh, worn hanging open.

Ensemble 5. Wool overcoat as for ensemble 4, but-toned up and with woolen scarf tied to block lapel opening; also leather gloves and hat as for ensemble 3.

Ensemble 6. Zippered quilted down-jacket extending to the trouser pockets and close-fitting at the wrists; also leather gloves and woolen hat as for ensembles 3 and 5.

Estimates of the conventional insulation values for these ensembles are given in table 3 in the Results section.

Posture

The manikin faced the wind squarely with its legs slightly apart, knees straight, feet on the floor, and arms hanging at its sides. It was suspended from the ceiling on a hook so that its weight was not on its feet, but the manikin did not move.

Procedure

The conditions were maintained until all sections were in stable equilibrium. Frequent returns to the same conditions were made to confirm repeatability. Temperature increments were about 2°C, and air velocity increases were 0.5 m/s with a minimum of 0.2 m · s⁻¹ to maintain temperature control. Within the limits of the tunnel, combinations were measured which resulted in total heat losses between 50 and 250 W · m⁻².

Results

Equations

Total heat loss in watts per square meter as a function of temperature (T) in degrees centigrade and velocity (V) in meters per second was found to be adequately predicted by an equation of the form:

$$W = A - B \times T + C \times V - D \times V \times T,$$

where A, B, C, and D are constants with different values for each ensemble. The correlation coefficients between the values predicted by the empirical equation and the actual measurements were greater than 0.99 in all seven cases. The values for A, B, C, and D are given in table 1, and the results are depicted graphically for each ensemble in figure 2.

Activity

Table 2 gives values of heat production for various activities, taken from the literature, and relative velocities typical for each activity. They conform to the approximate equation $W = 40 + 72 \times V$. For each ensemble, there is a neutral temperature at which the relative velocity for a given activity will result in a total heat loss equal to the heat produced.

Evaporative heat losses were neglected in relation to this study as they were likely to be very small compared with the thermogenesis required to maintain body temperatures under the conditions studied. The locus of neutral temperatures, relative velocities, and heat losses predicted by this equation is shown for each ensemble in figure 2.

Clothing insulation

Table 3 gives conventional clo values for each ensemble, calculated with the use of each equation to predict total heat loss at 0.1 m · s⁻¹, at a temperature giving a total heat loss of 50–90 W · m⁻² in each case. The temperatures considered appropriate were 20, 10, and 0°C, as shown in table 3. The clo value of the surrounding air was taken to be 0.7 in each case (at 0.1 m · s⁻¹). Calculating clo values at inappropriate temperatures, with predicted total heat losses outside the range of 50–90 W · m⁻², gave remarkably stable values for ensembles 0 and 6. The values decreased with temperature for the more wind-tight ensembles, but increased at lower temperatures for the least wind-tight ensembles (ensembles 1 and 4). The best estimates of clo value (table 3) were rank-ordered as expected from 0.51 to 1.90 clo, with increments of about 0.23 clo.

Wind effects

Table 4 gives some values of wind speed in meters per second that may be useful for matching predicted total heat loss to the heat production expected in various activities (table 2). Unless a given activity involves continuous movement into the wind, there is no need to

Table 2. Heat produced and outdoor activities at relative velocities. [$W \cdot m^{-2} = 40 + 72 \times V$, where V is air velocity ($m \cdot s^{-1}$)].

Activity	Heat produced ($W \cdot m^{-2}$)	Air velocity	
		$m \cdot s^{-1}$	$km \cdot h^{-1}$
0 Sitting	55	0.20	—
1 Standing	65	0.35	—
2 Strolling	80	0.56	2
3 Walking	120	1.11	4
4 Walking fast	160	1.67	6
5 Forced march	180	1.94	7
6 Jogging	220	2.50	9

add relative velocity to wind speed. In most activities it should just as often be subtracted, as one tends to walk, or run, in circles. Relative velocities are perhaps useful corrections for activities to be performed in otherwise still air.

Wind chill

The concept of a wind-chill equivalent temperature has been widely adopted and is familiar to many people, as it is often used by broadcasters. Siple & Passel's equation (3) is used to calculate the still-air temperature that would give the same wind-chill index value as the forecast combination of air temperature and wind speed. When clothing is chosen for outdoors, however, it may be assumed that most people are familiar with the effect of their own relative velocity and would allow for it. An air velocity of $2 m \cdot s^{-1}$ would therefore seem to be a more appropriate reference condition, corresponding to a fast walk (table 2) or a light breeze (table 4).

The forecast outdoor air temperature should be corrected for wind chill. Figure 3 has been devised for this purpose, with the use of the average values of A, B, C, and D given in table 1. Wind-chill equivalent temperatures, expressed as air temperatures which would result in the same total heat loss at $2 m \cdot s^{-1}$, were found to be almost the same for all seven ensembles, particularly at lower temperatures. Separate diagrams for each ensemble would be necessary to equate warmer conditions accurately, but this information is perhaps not as necessary. Figure 4 shows wind-chill equivalent temperatures for unprotected skin, again relative to $2 m \cdot s^{-1}$, as calculated by the Siple wind-chill index. It may be seen that wind-chill equivalent temperatures based on heat loss through clothing are much lower, even though the Siple index is for the rate of cooling of an unrealistically high skin temperature of $33^{\circ}C$. The equation used was the version given by McIntyre (4):

$$WCI = (10 \times SQR(V) + 10.45 - V) \times (33 - T),$$

where $SQR(V)$ is the square root of V .

Table 3. Thermal insulation (clo) estimated from equations at $0.1 m \cdot s^{-1}$, at a given temperature ($^{\circ}C$) and under the assumption that the insulation of air = 0.7 clo at $0.1 m \cdot s^{-1}$ (1 clo = $0.155 m^2 \cdot ^{\circ}C \cdot W^{-1}$)

Ensemble	Temperature ($^{\circ}C$)	Heat produced ($W \cdot m^{-2}$)	Thermal insulation (clo)
0 Shirt-sleeves	20	68	0.51
1 Sweater	20	48	0.89
2 Windbreaker	10	86	1.01
3 Windbreaker, augmented	10	72	1.34
4 Overcoat	0	98	1.45
5 Overcoat, augmented	0	89	1.68
6 Down-jacket	0	81	1.90

Table 4. Wind conditions in meters per second and kilometers per hour.

Condition	$m \cdot s^{-1}$	$km \cdot h^{-1}$	Observations
Wind still	0.2	—	None
Barely moving	1	3.6	Felt on face
Gentle breeze	2	7.2	Felt on face
Light breeze	3	10.8	Felt on face
Breeze	4	14.4	Clothes flap
Strong breeze	5	18.0	Flags outstretched
Quite windy	6	21.6	Tree branches in motion
Definitely windy	7	25.2	Dust and paper whirl up

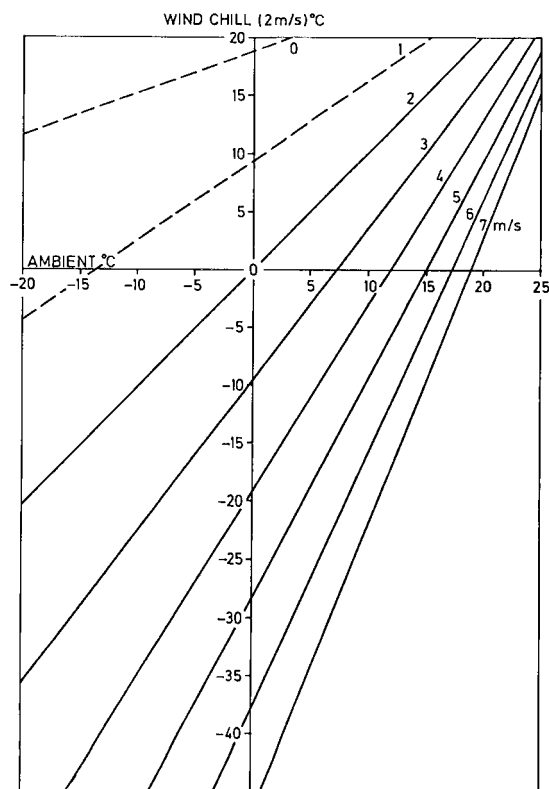


Figure 3. Wind-chill (equivalent heat loss) temperature (HLT) related to $2 m \cdot s^{-1}$, according to the average equation from table 1 [$HLT(2.0) = 18.6 - 9.28 \times V + (0.36 + 0.32 \times V) \times T$].

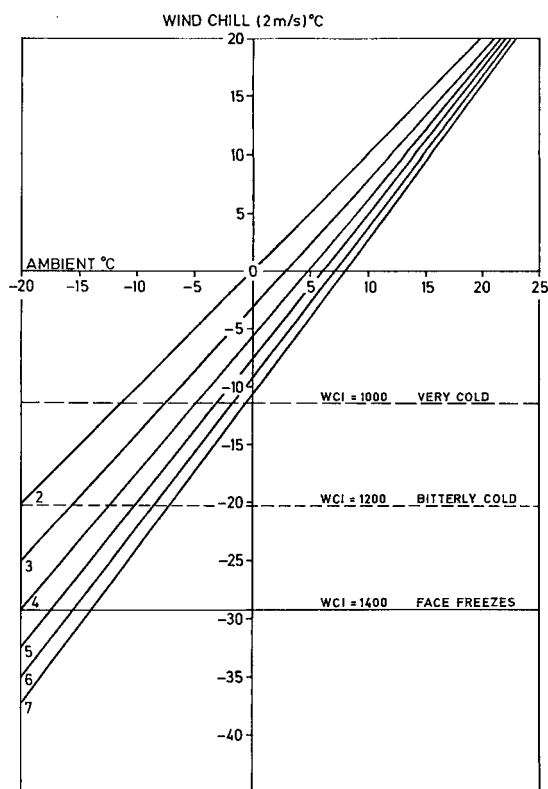


Figure 4. Wind-chill (equivalent index) temperature (WCT) related to $2 \text{ m} \cdot \text{s}^{-1}$, according to the Siple wind-chill index [WCT (2.0) = $33 + (T - 33) \times [0.44 \times \text{SQR}(V) + 0.46 - 0.44 \times V]$].

Discussion

The increased heat losses through clothing because of wind or relative motion are so high that the activities considered appear to have neutral temperatures down to only -3°C in still air [figure 2, ensemble 5 (forced march)], yet the ensembles are in common use for outdoor activities at temperatures down to -20°C . It is worth considering how this is possible.

First, it is normal to wear a sweater under the outer garment when it is sufficiently cold. On the assumption that the thermal insulation of a sweater is equivalent to 0.4 clo, the neutral range would be extended downwards by 7.4°C during normal walking ($120 \text{ W} \cdot \text{m}^{-2}$), and by 11.2°C during a forced march ($180 \text{ W} \cdot \text{m}^{-2}$). Additional garments such as boots and long underclothes might have an equivalent effect. Second, some decrease in average skin temperature is acceptable, though probably not more than about 5°C without severe discomfort. The neutral range would be extended downwards by this amount. Third, Benzinger et al (5) have shown that the physiological mechanism of thermogenesis can double bodily heat production at a skin temperature of 28°C , as core temperature falls by only 0.2°C in response to cold. Thermogenesis begins at a higher core temperature the lower the skin temperature and can thus anticipate body cooling to a greater extent the faster it tends to

occur. It is the safety mechanism of thermogenesis that ensures that one not only survives when uncomfortably cold but also returns with a healthy appetite due to the extra energy consumed.

In planning the outdoor environment, as in selecting a clothing ensemble, it is prudent to regard these physiological responses to cold as constituting a margin of safety should conditions become worse than expected. They have no effect on the wind-chill equivalent temperatures shown in figure 3. Field observations of the wind-chill equivalent temperatures at which people abandon various activities will be necessary to determine absolute levels, and the diagram can then be used to equate other combinations of wind and temperature. It seems likely that an inability to maintain whole-body heat balance will be more critical than facial discomfort below a Siple index value of 1200, designated "bitterly cold," in figure 3.

It should be noted that one can convert ensemble 2 to ensemble 3 by putting on the gloves and hat that one has prudently taken along. Ensemble 4 can be converted to ensemble 5 by buttoning up the coat and similarly putting on accessories. The neutral range of ensemble 6 can be extended upwards by opening the zipper. These aspects of clothing design are important in that they permit adaptation to changing weather and a wider range of activity level without clothes being changed. The present results make it clear, however, that the main source of adaptation under really cold conditions is to be found in the body itself.

Concluding remarks

Total heat losses through seven typical civilian outdoor clothing ensembles can be predicted by means of the empirical equations derived to fit the experimental data. Once either the relative velocity produced by the activity itself or the wind speed is taken into account, they can be used to select appropriate clothing for a given activity and temperature. Though very different from each other, all seven ensembles lead to very similar values of "wind-chill equivalent temperature," expressed as the air temperature that, in combination with a wind speed of $2 \text{ m} \cdot \text{s}^{-1}$, would result in the same total heat loss as would occur in the actual combination of air temperature and wind speed. Wind-chill equivalent temperatures calculated in this way for heat loss through clothing are much lower than those calculated with the Siple wind-chill index for unprotected skin. The Siple index does not take account of the penetration of clothing insulation by wind, and it therefore underestimates the cooling effect of wind at low temperatures for typical civilian outdoor clothing.

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Use of thermal manikins in environmental ergonomics

by David P Wyon, PhD¹

WYON DP. Use of thermal manikins in environmental ergonomics. *Scand J Work Environ Health* 1989;15(suppl 1):84–94. Thermal manikins are a fairly standard tool in environmental ergonomics. As they can provide a rapid, accurate, and reproducible simulation of the physical processes of dry heat loss to the environment, their main application is in the study of neutral or cold conditions at relatively low activity levels. Thermal manikins provide a good estimate of the total dry heat loss from the body and the distribution of heat flow over the body surface. In a standard environment, these measures can be used to describe the thermal characteristics of clothing. With standard clothing, complex thermal environments, eg, as in vehicles, can also be quantitatively compared and evaluated. Future developments include improved simulation of evaporative heat loss; improved software for simulating internal heat transfer, heat storage, and vasoconstriction; reactive programs with target total heat loss; empirical equations predicting manikin response to temperature, air velocity, etc; and standard techniques for testing diving and survival suits.

Key terms: clothing, cold stress, heat stress, HVAC, metabolism, thermal asymmetry, thermal insulation, thermal profiles, vehicles.

Three main areas of application may be identified for thermal manikins — clothing, HVAC (heating, ventilation, air conditioning), and thermal physiology. The clothing and HVAC industries exist to develop and mass-produce artifacts that compensate for the inadequacies of the human thermoregulatory system — to adjust the microclimate to humans. This topic is the concern of environmental ergonomics, and my paper describes ways in which thermal manikins can be used in these two industries.

The thermal physiology “industry” exists to investigate the function of the human thermoregulatory system. Human subjects will always be the focus of this work, by definition, whereas the focus of the clothing and HVAC industries is the product. The function of the product can often be adequately described, measured, and improved with the use of thermal manikins in bridging the gap between the simplifications of scientific theory and the complexities of the real world. The mathematical models currently in use to describe human thermoregulatory response are so oversimplified that they are valid, even in theory, only for homogeneous environments. They cannot adequately take account of such aspects of clothing as the distribution of insulation over body sections, drape, fit, pumping, internal convection, penetration by air movement or wind, compression of insulating fabric layers, moisture diffusion, phase change and wicking (capillary moisture transport) or such aspects of HVAC as air temperature gradients, radiation asymmetry,

solar radiation on some sections of the body but not on others, air speed, direction and turbulence, deflection of air currents by the body, self-convection, posture, thermal characteristics of seats, submaximum sweating, wet shoes, or wet clothing. In the future thermal manikins may be of considerable use to thermal physiology by providing accurate and reproducible assessments of these effects on heat loss from the skin surface, but the use of thermal manikins in the further development of thermal physiology theory is not the subject of this paper.

Human heat balance in theory and in practice

Human heat balance in a homogeneous thermal environment is affected by air temperature, thermal radiation temperature, air velocity, and humidity. These quantities can be measured by means of physical sensors, each reading at a specified point. Few real environments are even approximately homogeneous, and even the climate chambers used for studies of human heat balance under homogeneous conditions are defective in that vertical thermal gradients are difficult to eliminate without vigorous mixing of the air, such vigorous mixing implying high air velocities and turbulence. The most usual climate chamber alternative, displacement ventilation achieved by air supplied through a perforated ceiling, floor, or wall, establishes an approximate laminar flow with an average air velocity of $0.1\text{--}0.2\text{ m}\cdot\text{s}^{-1}$. This level of velocity allows self-convection to take place over the body surface under most conditions of exposure — the upper body losing less heat to the environment to the extent that it is surrounded by a layer of slowly rising air, warmed by the lower sections of the body and increasing in thickness with height above the floor. Thus,

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even under artificially homogeneous conditions, the body experiences a degree of inhomogeneity (asymmetry) of heat loss that is not reflected in conventional measures of the thermal environment, even if they are repeated at a number of points within the volume to be occupied by the human body.

Self-convection is greatly modified by posture. When one lies down on a suspended net, all sections lose more heat, whereas a mattress insulates contact surfaces and blocks upward airflow so that heat losses are reduced. When one is seated, the detailed design of the chair exerts a very large effect. It can cause self-convection air currents to be blocked and be responsible for insulating up to 20 % of the body surface area. Self-convection while a person is seated leads in general to reduced heat loss from the front of the body and increased heat loss from the back, as heat originating from the legs now passes in front of the body. The exact position of the arms and legs in relation to the trunk and to each other is also influential.

Clothing modifies the effects of posture, self-convection, and insulation by mattresses and seats. In view of these complexities, one is not surprised to find that thermal physiologists often choose to study the thermoregulation of naked subjects lying on a suspended net with arms and legs extended, in the center of an elaborate climate chamber. Under these circumstances, measurement of the four thermal parameters will accurately predict human heat balance. Equations based on such studies, taking account of metabolic heat production as well, have hitherto represented the insulation provided by clothing with a single number (the clo value), and they have ignored the effects of posture, seat insulation, self-convection, thermal gradients, and the spatial and temporal variation of air velocity. They thus, in effect, describe the heat balance of a 30-inch sphere (0.76 m diameter, surface area 1.8 m^2) suspended in a homogeneous environment, insulated with a uniformly thick layer over the entire surface, and rotating slowly to counteract the effects of self-convection. Environmental ergonomists should keep this underlying physical model in mind when choosing between an apparently sophisticated index requiring the input of conventional physical quantities and an apparently crude measure such as wet bulb globe temperature (WBGT), which is based on the empirically measured heat balance of a six-inch (15.24 cm) sphere and that of a thermometer in a wet sock (as recommended for hot environments both by the National Institute for Occupational Safety and Health and by current standards of the International Organization for Standardization).

Evolution of thermal manikins

Measurement of any one physical parameter of the environment is usually affected by another — thermometers purporting to measure air temperature must be aspirated and screened from thermal radiation, wet-

bulb thermometers must be protected from air velocity, anemometers must be corrected for air temperature, etc. As there is some doubt as to how the “unbiased” measurements are to be combined to predict human heat balance, it is tempting to select some thoroughly biased sensor, such as a globe thermometer, and simply assume that its uncorrected reading is affected by air temperature, air velocity, and thermal radiation in the same way as the human body.

This is a very big assumption, and, even if it were true, it does not take into consideration the influence of clothing, posture, self-convection, and the problem of how to combine readings taken at different points within the volume to be occupied by the human body if they should turn out to differ. Uncorrected physical sensors cannot be regarded as the “missing link” in the evolution of thermal manikins. There is a similar dichotomy between flat-plate instruments for measuring the properties of textiles, and thermal manikins capable of wearing finished clothing.

The use of thermal manikins, in common with many other ergonomic techniques, appears to have sprung, fully fledged, from the military ergonomics laboratories of World War II, when scientists were forced by the pressure of military necessity to cut short their development of theory and devise ways of making valid and practically useful assessments of human heat balance in complex thermal environments. Gonzales et al, in their as yet unpublished report “The Relative Applications of Predicting Effects of Environmental Clothing and Personal Equipment on Military Operations,” cited parallel developments of single-section copper manikins for assessing military clothing at, eg, the Harvard Fatigue Laboratory, the JB Pierce Laboratory, and the Quartermaster Climatic Research Laboratory (personal communication). Winslow, Herrington, and Fitzgerald were all associated with this work in the 1940s. Some of the manikins, constructed by the General Electric Company and the Bridgeport Brass Company, are apparently still in use. Their total heat loss can be measured as a function of the clothing they wear and the environment in which they are placed. Their use is limited in that they have only one posture and they do not map heat flow to the environment over the body surface. They are the precursors of modern thermal manikins that do not have these limitations. In complex thermal environments, and for clothing assessment, they are considerably more useful than the physical instrumentation that preceded them.

Many attempts have been made to increase the multifactor bias of conventional instruments through the heating of sensors to increase their sensitivity to air velocity and make their response to thermal radiation resemble that of the human body. The “eupatheoscope” mentioned by Bedford (1) was perhaps a precursor of thermal manikins — it was a large heated cylinder on legs — except that it could not wear clothing. Its very arbitrary measurements found little prac-

tical use. The "heated cigar" of the Comfy Meter[®] developed at the Danish Technical University by Lund-Madsen and now marketed commercially (Brüel & Kjaer) appears at first sight to be a contemporary example of the same principle, but the associated analogue circuitry causes the reading to correspond to the rational heat balance equation proposed by Fanger (2). Estimates of clothing insulation, metabolic rate, and humidity must be entered by hand. The Comfy Meter[®] is a hybrid — an analogue computer with a digital display, a theoretical model of human heat balance with a "multifactor biased" direct measurement of the combined effect of three out of six parameters. The shape of the heated cigar has the same angle factors as a rotating human body, and the heat balance predicted is that of the uniformly insulated, rotating 30-inch (76.2 cm) sphere of thermal physiology theory. Its use neglects the detailed effects of clothing, seats, posture, and the deflection of air currents by the body, and the problem of combining measurements made at a number of points within the volume to be occupied by the human body remains. It would be a useful "miniature manikin" in a scale model of a thermal environment, but it does not appear to have been used in this way.

Another candidate for the label of "missing link" came into operation in 1986, ie, the heated sweating cylinder used by the Finnish Textile Laboratory to study the problem of ice formation in multilayer clothing during heavy work in extreme cold (3). It cannot wear complete garments, but the effect of complete garments on the torso may be closely simulated. Sweat is produced at a controlled rate through a Goretex[®] membrane, whose temperature is independently controlled. This apparatus is useful in itself, but can be regarded as a design study for the sweating manikin "COPPELIA," which is now nearing completion.

Existing equipment

Table 1 presents data on the thermal manikin systems which, to my knowledge, are in operation in 1988. Water-filled torsos, severed limbs, assemblies of cylinders or boxes, such as ALU-MARGRETE (Danish Technical University), and early prototypes, some now in technical museums, such as HENRIK 1 (Danish Technical University), have been omitted. The approximate year when the first manikin of each series came into operation is given, along with mention as to whether each manikin can sit or stand. None of the manikins currently in operation can simulate sweating at a controlled rate that results in thermal equilibrium, although some have been used to simulate sweating, a cotton body-stocking being sprayed with distilled water before more clothing is added, and most of them could be used in this way. It can be seen that the number of sections with independent control of skin temperature is usually 16—19. Data obtained with

the only two manikins that have more sections are usually combined into 16—19 sections before presentation. Manikins built prior to 1980 are controlled manually or by simple on-off regulators or analogue control circuits. With the advent of microprocessors and microcomputers, later manikins are usually controlled digitally, the regulators then consisting of software algorithms. The proportional, integral, and differential components of the feedback loop can then more easily be optimized for each section to achieve rapid and stable control. Software calibration, on-line analysis, and more sophisticated on-line displays become feasible with digital computer control.

The main applications for which each manikin system is used are also indicated in table 1 in descending order of priority, so far as is known. Seventeen manikins are used primarily for clothing measurement, four primarily for measuring the microclimate produced by the heating, ventilating and air-conditioning of buildings, and four exclusively for measuring the microclimate of vehicles, a total of 25 in all.

It is important to note that although all the manikins articulated at the hip have been marked as capable of sitting, they do not sit very well. Their seated posture and their contact with the base and back of a seat are never satisfactory for measuring the thermal characteristics of seats. The shapes of manikins incapable of standing have been optimized for this purpose, and their contact surfaces are controlled as separate sections.

Table 1 also gives some details of three new manikin systems nearing completion — two of them capable of controlled sweating (numbers 26 and 27) and one similar to existing manikins except that it will have a female shape. All previous manikins have been intended to fit men's clothing, while invariably allowing modesty to prevail over verisimilitude.

Standardization

Due to the variety of applications, the widely differing budgets, and the 40 years of development represented by the systems, the 23 manikins in table 1 are not identical, and the question of measurement standardization is important. In the case of clothing measurements, McCullough & Wyon (4) obtained the same clo values with SAM and SIBMAN, once allowance was made for SAM's bald pate, and showed that skin temperature distribution was not a critical factor. A recent comparison of four manikin systems (5) confirmed this point and showed good agreement between the TORE and HENRIK series for a range of clothing insulation. However, the influence of fit was found to be very considerable. SIBMAN, which should have had clothing several sizes smaller than the other manikins, returned considerably higher clo values. Ensuring that the garments to be tested actually fit the manikin to be used is almost certainly the major prob-

lem of standardization in practice. It is for this reason that the TORE series was made to fit a standard Scandinavian clothing size from the start. Measurements of female clothing on existing (transvestite) manikin systems should therefore be treated with caution.

Principles of operation

The principle of operation of all of the manikins in table 1 is to achieve a stable dynamic equilibrium with the thermal environment and to measure the heat flow

Table 1. Existing thermal manikins.^a

Number	Completion date of original model	Name	Affiliation	Sit	Stand	Number of sections	Control ^b	Use ^c
<i>In operation in 1988</i>								
1	1945	SAM	United States Army Research Institute for Environmental Medicine, Natick, Massachusetts, United States	No	Yes	1	M	C
2	-	-	Institute for Environmental Research, Kansas State University, Manhattan, Kansas, United States	No	Yes	1	M	C
3	1964	ALMANIKIN	Royal Air Force Institute of Aviation Medicine, Farnborough, Hampshire, England	No	Yes	11	R	C
4 ^d	-	-	The Cord Group, Dartmouth, Nova Scotia, Canada	No	Yes	13	D	C
5	1972	CEPAT400	Laboratory for Environmental Physiology and Psychology, National Center for Scientific Research, Strasbourg, France	Yes	Yes	1	R	C
6	1973	HENRIK 2	Laboratory for Thermal Insulation, Danish Technical University, Lyngby, Denmark	Yes	Yes	16	A	C, H
7	-	-	Institute of Occupational Health, Helsinki, Finland	Yes	Yes	16	A	C
8	1978	CHARLIE	Hohensteiner Institute, Schloss Hohenstein, Bonnigheim, Federal Republic of Germany	Yes	Yes	16	A	C
9	-	-	Multi-tech Corporation, Natick, Massachusetts, United States	Yes	Yes	16	A	C
10	1980	SIBMAN	National Swedish Institute for Building Research, Gävle, Sweden	Yes	Yes	16	D	H, C
11	1982	VOLTMAN	National Swedish Institute for Building Research, Gävle, Sweden	Yes	No	19	D	H, S, C
12	-	-	Volvo Car Corporation, Göteborg, Sweden	Yes	No	19	D	V
13	-	-	Volvo Car Corporation, Göteborg, Sweden	Yes	No	19	D	V
14	-	-	Volvo Truck Corporation, Göteborg, Sweden	Yes	No	19	D	V
15	-	-	General Motors Corporation, Detroit, Michigan, United States	Yes	No	19	D	V
16	-	-	Hungarian Institute for Building Science, Budapest, Hungary	Yes	No	19	D	H, S, C
17	-	-	Hungarian Institute for Building Science, Budapest, Hungary	No	Yes	17	D	C, H
18	1984	TORE	National Swedish Institute for Building Research, Gävle, Sweden	Yes	Yes	18	D	C, H
19	-	-	Textile Research Institute, Göteborg, Sweden	Yes	Yes	18	D	C
20	-	-	Institute for Environmental Research, Kansas State University, Manhattan, Kansas, United States	Yes	Yes	18	D	C, H
21	-	-	TNO Institute for Perception, Soesterberg, Holland	Yes	Yes	18	D	C
22	-	-	Textile Laboratory, Technical Research Center of Finland, Tampere, Finland	Yes	Yes	18	D	C
23	1985	ASSMAN ^d	National Swedish Institute of Occupational Health, Solna, Sweden	Yes	No	36	D	C, H, V
24	1986	A LITTLE	United States Army Research Institute for Environmental Medicine, Natick, Massachusetts, United States	Yes	Yes	19	D	C
25	1987	HEATMAN	VIAK Corporation, Falun, Sweden	Yes	Yes	36	D	H
<i>Nearing completion in 1988</i>								
26	?	COPPELIA	Textile Laboratory, Technical Research Center of Finland, Tampere, Finland	Yes	Yes	18	D	C
27	?	MANNY	Batelle Corporation, Richland, Washington, United States	Yes	Yes	18?	D	C
28	?	PERNILLE	Laboratory for Thermal Insulation, Danish Technical University, Lyngby, Denmark	Yes	Yes	16	D	C

^a Several manikins are apparently in operation in Japan.

^b M = manual; R = on-off regulator; A = analogue; D = digital computer.

^c C = clothing; H = heating, etc; V = vehicles; S = seats.

^d ASSMAN is now known as AIMAN.

to or from the environment at equilibrium, skin temperature being accurately known regardless of whether or not it is controlled to preset values.

Heating

All but one of the manikins are electrically heated. The heat supplied can therefore be accurately controlled and measured in most cases to within 0.002 of the maximum rated power input to each section. The power may be dissipated internally, as in the SAM and HENRIK series, or subcutaneously, as in the VOLTMAN and TORE series. Depending on application, the power rating of each section can be up to $2000 \text{ W} \cdot \text{m}^{-2}$. Stability becomes a problem if maximum power to a section is grossly overrated. HENRIK was originally heated by means of miniature hot-air blowers in each section. When servicing these units became a problem, the system was changed. Resistive wire was evenly distributed in good thermal contact with the inside surface of each section. In TORE and VOLTMAN, heating wires are placed in grooves cast or machined into the external surface of each section. It is necessary to use Constantan resistance wire to avoid errors due to local overheating and resistance change and to use many different gauge wires. If one gauge is used throughout, small sections will have low resistance and very high power ratings per square meter. For large sections the situation will be reversed.

The manikin without electrical heating is that of the Centre d'Etudes de Physiologie Appliquée au Travail (CEPAT) described by Lebrun & Lecarpentier (6). It is heated or cooled by means of water circulating in pipes brazed to the inside surface of each copper section. The CEPAT manikin was designed to maintain a skin temperature of 35°C in a 400°C environment. It is mainly used to measure the insulation of protective clothing for extremely hot environments.

Conducting layer

Between the heating layer, however constructed, and the outer surface, there is usually a conducting layer to ensure an even surface temperature. The SAM, the CEPAT, and the A LITTLE manikins are actually made of copper, and ALMANIKIN of aluminum, whereas most of the rest have conducting layers of electro- or thermo-deposited copper or aluminum sandwiched between layers of plastic and fiber glass.

Measurement

The HENRIK and the CEPAT manikins measure internal temperature and calculate surface (skin) temperature from a knowledge of heat flow and surface resistance, both of which are assumed to be evenly distributed over the surface of each section. Other manikins measure skin surface temperature directly by means of resistive sensors, usually nickel or cadmium wire. If these sensors are several meters long and evenly

distributed over the surface of each section, a reliable estimate of skin temperature is obtained. These sensors are vulnerable to mechanical damage and constitute the major weakness of most manikins in practical use, as they must be at or very close to the actual surface. Mechanical damage to these wires can even result from severe frost or heat exposure, eg, during transport, due to the expansion and contraction of the surface. (See the Calibration section.)

Control

The power input can be controlled through the altering of the voltage, through the use of analogue circuits or digital/analogue convertors, or through the maintenance of a constant voltage and the pulse coding of the input current. In the last case it is essential to have extremely rapid switching transistors to ensure square-wave pulses whose shape is not load dependent. Power-supply units should also have remote-sense inputs to eliminate load-dependent cable losses. Only with these precautions can accuracies of 0.002 of the maximum power rating be routinely achieved over the whole working range.

Analysis

Voltage measurement, or counting pulses over a fixed integration period, together with a knowledge of the (preferably constant) internal resistance, yields a total power input value for each section in watts. Before this input value can be converted to watts per square meter, accurate knowledge of the heated surface area of each section is required. This information is best obtained if the amount of masking tape used to cover each section completely is weighed to an accuracy of 0.01 g. If the same technique is used on a cylinder of known surface area and both procedures are repeated an adequate number of times, requisite accuracy can be achieved. It need only be done once for each manikin series, ie, if manufacturing procedures are assumed to be accurate.

Total power input for the manikin, divided by its total surface area, usually close to 1.8 m^2 (the value for an average European male), gives total heat loss in watts per square meter. The area-weighted mean skin temperature minus the environmental operative temperature, divided by the total heat loss, yields the accepted standard unit for total clothing and air insulation (in $^{\circ}\text{C} \cdot \text{m}^2 \cdot \text{W}^{-1}$). Division by 0.155 converts this value to the clo unit (7). The TORE series displays this value, and similar values for each section, as a continuously refreshed table of values. It is then possible to alter the drape and fit of a garment and to see the results immediately in these terms, or to see the effect of adding or subtracting a garment. Color changes are used to indicate whether a particular value is changing or stable; therefore removing a jacket causes an immediate color change for the affected sections. The display returns to monochrome when the values are

reliably stable. A similar visual feedback is used if any section has reached the maximum or minimum power rating, as the equilibrium is then spurious. The analysis of measurements made by earlier manikins was off-line and fairly time-consuming, and this kind of optimization and learning by instant feedback was inhibited. Similar advances in the analysis and presentation of results for microclimate optimization follow.

Calibration

Skin temperature sensors must be calibrated against reference thermometers with the manikin passively exposed (unheated) to a number of homogeneous environments at different temperatures in the range of 30–35°C. This procedure is usually carried out in a climate chamber. The VOLTMAN series has an auto-calibration facility which achieves an accuracy that is an order of magnitude better even under field conditions. The manikin is placed in an air-freight container which is well-insulated and fitted with a 24-V truck fan. The manikin process controller adjusts the speed of this fan continuously to achieve a series of very accurately controlled air temperatures in the box while maintaining very high air velocities around the manikin. The resistance of each of the 19 skin temperature sensors is read when each stable condition has been maintained for 3 h. New regression equations are calculated automatically and stored.

This completely automatic sequence takes about 12 h and can be carried out during the night in a workshop or even in a hotel room on vehicle test expeditions. This possibility eliminates measurement errors due to mechanical damage to sensors during transport or in field use. Skin temperatures must be measured and controlled to within 0.1°C to achieve sufficient accuracy in heatflow measurements. Voltages, currents, and resistances can of course be measured with standard instruments, and such measurements should be repeated at intervals.

Reference exposures

A key concept in thermal manikin measurement is that of the reference exposure under standard conditions. In clothing measurements, this procedure takes the form of a reference exposure without clothing to distinguish between the insulation of the clothing and that of the air surrounding it. In measurements of microclimates, a reference exposure is necessary before heat flow can be expressed in terms of the equivalent homogeneous temperature (EHT), ie, that temperature which, in the reference exposure, produced the same heat flow from the section in question. Thermal manikins find their main use in complex thermal environments, where the degree of thermal asymmetry must be quantified to reduce or eliminate “drafts,” ie, excessive cooling of certain body sections. While the sensation of losing 100 W · m⁻² is not familiar to most people, expressing the same value as an equivalent

homogeneous temperature of 15°C on the basis of a reference exposure makes it easier to assess. A suitable reference environment, as used by me for VOLTMAN, is one in which all surfaces approximate to air temperature, humidity is constant, thermal gradients in all three directions are very low, and air velocities are so low (<0.1 m · s⁻¹) that the self-convection of the manikin is unaffected when visualized by the use of smoke. The manikin is supported in a seated posture on a wide-mesh net seat that compresses the clothing but does not insulate the contact surfaces. A typical car seat will then reduce heat flow from contact surfaces so much that equivalent homogeneous temperatures above 30°C are obtained in a 22°C environment. Only one reference condition is strictly required, as heat flow is linearly related to the equivalent homogeneous temperature and is zero when the environment is at skin temperature. The results of the reference exposure are regression equations relating heat flow in watts per square meter to the equivalent homogeneous temperature. They are calculated, stored, and used on-line (8).

Documentation

There are no accepted conventions for depicting the asymmetry of a clothing ensemble. Clo values are usually quoted only in terms of the effect on whole-body heat balance. TORE provides an on-line table of sectional clo values, as has already been described, which may be output on paper. For microclimate assessment, my co-authors and I have proposed a standard form of presentation in terms of an “EHT profile” (9). It has already been used for the thermal environment of the driver’s seat of city buses (10), in offices with displacement ventilation (11), in comparisons of the on-off and proportional-integral regulation of air-conditioning (12), and on a routine basis for vehicle work by the Volvo and General Motors companies (restricted-circulation internal reports). Figure 1 shows an example of such a diagram. The body sections are listed in order from head to foot, in left-right sequence where applicable, those in contact with the seat being shown separately. Vertical asymmetry is apparent in the general slope of the profile, while lateral asymmetry gives rise to a “saw-tooth” profile.

Assessment

Total dry heat loss in watts per square meter may be compared with target values derived from physiological measurements of metabolic heat production and evaporative heat loss. For sedentary activities such as office work or driving, it is my experience that a discrepancy of only 5 W · m⁻² in either direction from thermoneutrality gives rise to a definite feeling of whole-body discomfort after 15–20 min. Physiological measurements of total dry heat loss are usually quoted to the nearest 10 W · m⁻², due to inaccuracies of measurement, the assumptions involved in oxygen

uptake analysis, and the uncertainty as to how much extra effort is required for mask breathing during such measurements. Thermal manikin measurement of whole-body heat loss in a given thermal environment, however complex, can be made with an accuracy that is an order of magnitude better, and, when combined with human subjective assessment of thermoneutrality, it may actually be the most accurate and reliable way of assessing metabolic rate in such circumstances. A value of $47.2 \text{ W} \cdot \text{m}^{-2}$ was found for 72 subjects performing office work (11); it corresponds very closely to 1 MET ($58 \text{ W} \cdot \text{m}^{-2}$) with 80 % dry heat loss.

Sectional dry heat loss, recalculated as the equivalent homogeneous temperature, must also be assigned a target value and an acceptable range. These values may differ for different body sections. For vehicle drivers and passengers, my co-workers and I (9) have proposed (i) ideal profiles (IP) that differ considerably between winter and summer, (ii) acceptable ranges, ie, vehicle comfort regions (VCR), that differ for drivers and passengers, and (iii) the use of a “figure of merit,” ie, the standard deviation of the equivalent homogeneous temperature from the relevant ideal profile (SDIP). The recommended values are based on five years of experience with VOLTMAN in vehicle research and development and on a direct experimen-

tal comparison of manikin and human response in the vehicle environment. Figure 2 is an example of an EHT profile diagram in which the vehicle comfort region appears as a “piste,” and the ideal profile as a slalom track down it. The designer of the thermal environment of the vehicle attempts to avoid going “off-piste” under specified critical operating conditions, and his adherence to the ideal profile is quantified as the standard deviation from the ideal profile. These diagrams, available on-line or directly after a wind-tunnel or field trial, greatly facilitate the development of empirical solutions to vehicle climate deficiencies. They make a quantitative comparison of competing designs or vehicles possible in terms of environmental ergonomics rather than in terms of physical and engineering quantities. Figures 3—5 are further examples of the use of this method of documentation.

If these methods of depicting and assessing thermal asymmetry were applied also to clothing, two fields of research and development, at present the preserve of very different specialists, would be brought together. Environmental ergonomists must, in practice, regard protective clothing and environmental modification as alternative and sometimes complementary solutions to human heat balance problems. The thermal insulation measurements provided at present by clothing spe-

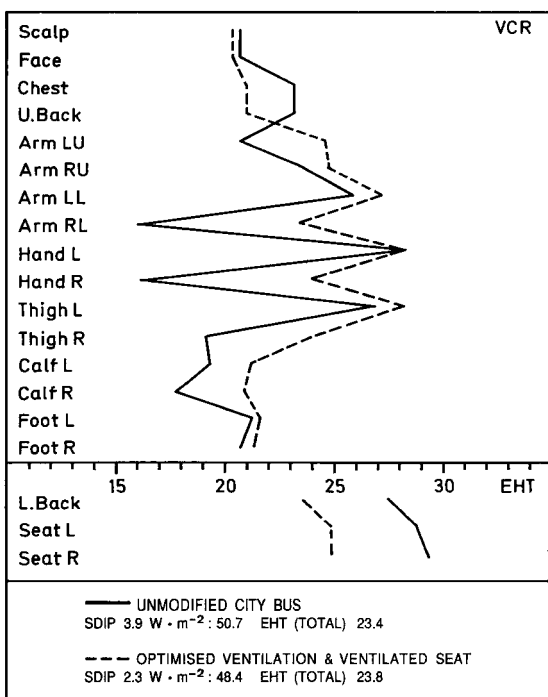


Figure 1. Profile diagram for a bus driver in full sun — effect of optimized ventilation and ventilated seat. (VOLTMAN = name of manikin used, U = upper, LU = left upper, RU = right upper, LL = left lower, RL = right lower, L = left, R = right, L Back = lower back, EHT = equivalent homogeneous temperature, SDIP = standard deviation from ideal profile)

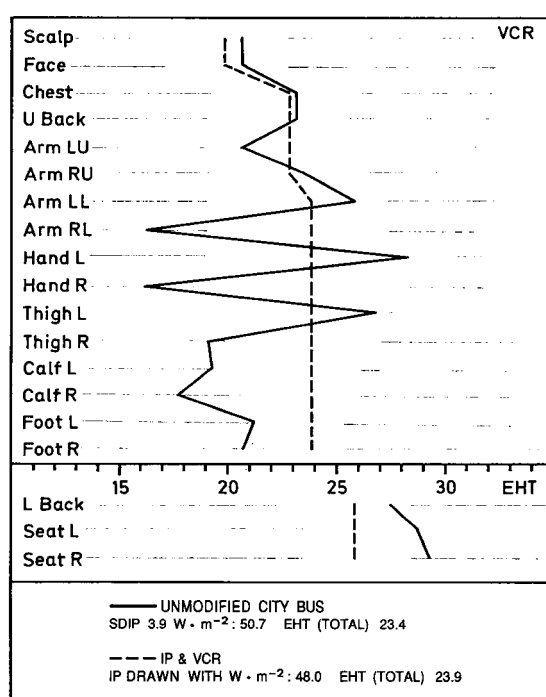


Figure 2. Profile diagram for a bus driver in full sun — unmodified city bus. (VOLTMAN = name of manikin used, VCR = vehicle comfort regions, U = upper, LU = left upper, RU = right upper, LL = left lower, RL = right lower, L = left, R = right, L Back = lower back, EHT = equivalent homogeneous temperature, SDIP = standard deviation from ideal profile, IP = ideal profile)

cialists (where each garment is assessed only in terms of its contribution to whole-body thermal insulation) are not adequate for this purpose. An insulated jacket may well have the same conventional clo value as a pair of insulated trousers. In a real situation, with drafts, cold seats, thermal gradients, and direct sunshine, they do not result in the same sensations. Clothing designers need better information on the effects of their products if they are to play their part in correcting the thermal deficiencies of problem environments.

Prediction of thermal discomfort

Total dry heat loss is probably the best available predictor of whole-body thermal discomfort, and I have found sectional dry heat loss to predict sectional thermal discomfort with correlation coefficients in excess of 0.8 (11). A linear relationship between the equivalent homogeneous temperature and the mean thermal vote (MTV) has invariably been found where the mean thermal vote is based on the 7-point Bedford scale in which -3 is assigned to "much too cold," -2 to "too cold," -1 to "comfortable but cool," 0 to "ideal," and so on, applied to sectional thermal discomfort by

asking subjects to fill in these figures on a diagram of the body divided into sections corresponding to those of the manikin. It has been found that, although there appears to be a stable sigmoidal relationship between mean thermal vote and the percentage of "too hot" and "too cold" responses in different populations providing these responses, subjects will accept a greater degree of asymmetry in a vehicle than in a building, ie, the slope of the EHT/MTV regression differs between these contexts in our data.

Physical indices of the equivalent homogeneous temperature

The equivalent homogeneous temperature is a purely physical measurement, but a complex and expensive thermal manikin system is required to obtain it. It is sometimes useful to derive empirical indices that predict sectional EHT values in a given context in terms of the relevant physical parameters. This procedure has been carried out by Wyon & Sandberg (11) for the unusual thermal environment created by displacement ventilation in offices; it has enabled engineers to compare diffusers, flow rates, etc, in terms of temperatures and air velocities, while ensuring that the EHT

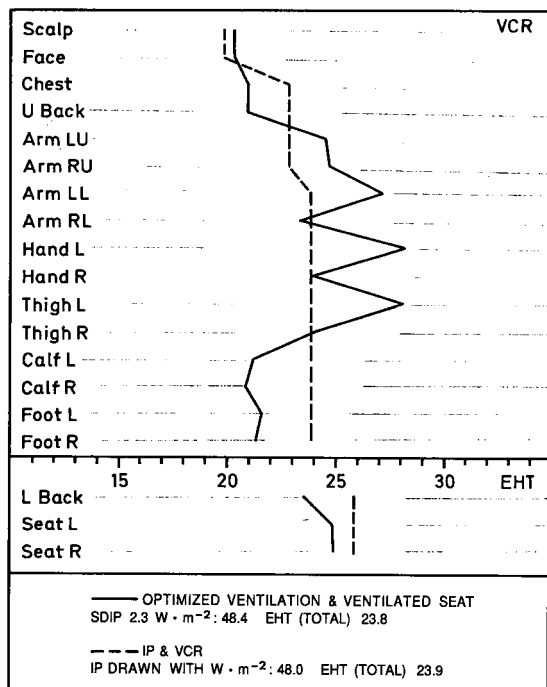


Figure 3. Profile diagram for a bus driver in full sun — optimized ventilation and ventilated seat. (VOLTMAN = name of manikin used, VCR = vehicle comfort regions, U = upper, LU = left upper, RU = right upper, LL = left lower, RL = right lower, L = left, R = right, L Back = lower back, EHT = equivalent homogeneous temperature, SDIP = standard deviation from ideal profile, IP = ideal profile)

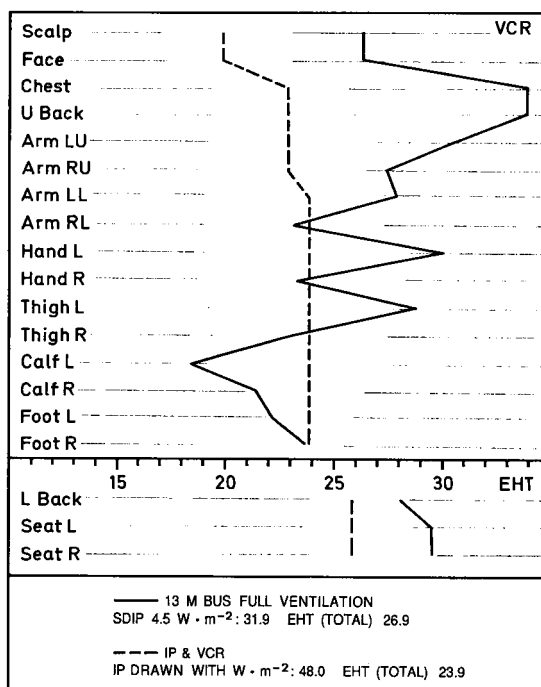


Figure 4. Profile diagram of the ideal profile (IP) and vehicle comfort regions (VCR) of the microclimate of a city bus driver's seat — example of a city bus. (VOLTMAN = name of manikin used, U = upper, LU = left upper, RU = right upper, LL = left lower, RL = right lower, L = left, R = right, L Back = lower back, EHT = equivalent homogeneous temperature, SDIP = standard deviation from ideal profile)

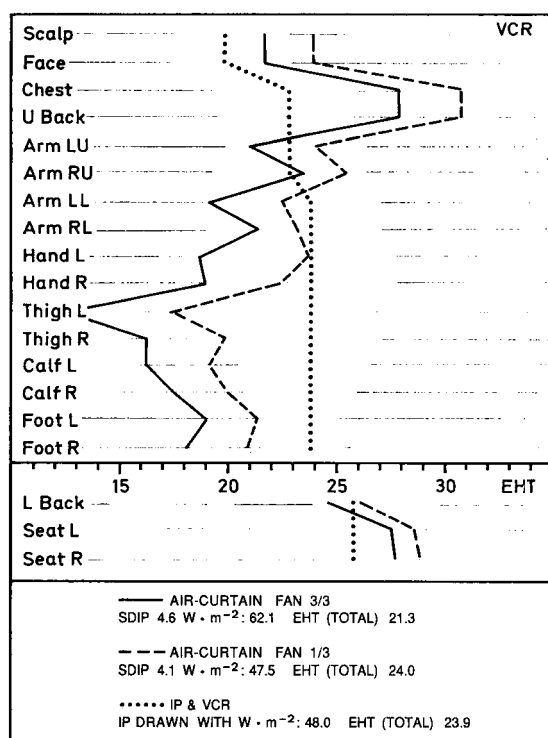


Figure 5. Profile diagram of the ideal profile (IP) and the vehicle comfort regions (VCR) of the microclimate of a city bus driver's seat — experimental air-curtain bus. (VOLTMAN = name of manikin used, U = upper, LU = left upper, RU = right upper, LL = left lower, RL = right lower, L = left, R = right, L Back = lower back, EHT = equivalent homogeneous temperature, SDIP = standard deviation from ideal profile)

values remain within comfortable limits derived in a laboratory comparison of human and manikin response. Such indices should only be applied to contexts in which the EHT profile may be expected to have a similar appearance, ie, contexts presenting the same kind of thermal asymmetry. Another example of a physical index based on thermal manikin response is total manikin heat loss predicted in terms of air temperature and wind speed (13).

Special applications

In addition to their use in assessments of clothing, HVAC solutions for buildings and vehicles, and outdoor environments, thermal manikins capable of measuring dry heat loss have been used in a number of special applications, eg, to assess humidity transients in clothing (14), to resolve conflicts between the thermal requirements of patients and staff in hospital wards (15), to quantify pumping effects in clothing (16), to assess the alleviation of solar load on vehicle occupants through the use of reflecting glass windows (Norin et al 1987, Volvo internal report), to assess electrically heated seats (Larsson et al 1988, Volvo internal report),

and to develop a ventilated seat for city bus drivers (10).

Evaporative heat loss

When total dry heat loss, as measured on a thermal manikin, is less than the metabolic rate for the activity under study, the discrepancy is an accurate estimate of the evaporative heat loss required and may be expressed as a required sweat rate in liters per hour. In situations in which there is some doubt as to whether it would be possible to achieve thermal equilibrium by sweating, it would be desirable to simulate sweating with a thermal manikin so as to be able to optimize the evaporative cooling power of the clothing, seat, and environment combined. No manikin capable of simulating sweating has yet been built (table 1), but a project to construct such a manikin is nearing completion in Finland. The COPPELIA manikin will be a TORE manikin with a Goretex[®] membrane skin and over 200 sweat glands individually controlled by a computer. Capillary material bonded onto the back of the Goretex[®] membrane spreads the distilled water released by each gland. At sweat rates below the effective maximum the "skin wettedness" will be both incomplete and somewhat unnatural. In addition, assessing the vapor diffusion resistance of the clothing barrier is dependent on measurements of air humidity in the very small volume between skin and clothing and is difficult. However, even without such measurements, the trials would provide a fairly good empirical simulation of human heat balance to verify whether a given sweat rate is possible. If quantitative assessment of the vapor diffusion resistance of an ensemble is required, it can be done by means of an iterative procedure in which sweat rate is increased and decreased to find the minimum value at which maximum total heat loss is achieved. As equilibrium must be achieved at each trial value of sweat rate, the procedure will be lengthy, and it must be repeated without clothing. Supplementary measurements of total dry heat loss with and without clothing, with zero sweat rate, when combined with the two values of maximum effective sweat rate, enable evaporative heat loss to be distinguished from dry heat loss, and the vapor diffusion resistance of the clothing to be distinguished from that of the environment. The sweating cylinder developed in Tampere has already been found useful in this way, and the COPPELIA system will make this kind of measurement possible for complete ensembles.

Future developments

Thermal manikin techniques have already developed to the stage where a great diversity of applications is possible and very likely in the near future. Total heat loss affects human performance, and therefore also safety, while sectional heat loss determines comfort,

draft sensation, and the risk of cold-related muscular injury. Thermal manikins provide the specific feedback necessary to be able to optimize a complex thermal environment rapidly and effectively with the use of protective clothing or environmental modification. Several very different solutions can be quantitatively compared, and, if they produce the same result, the most economic can be selected. Environmental controls can be adjusted to provide constant manikin response (ie, the equivalent homogeneous temperature) rather than constant air temperature, and this is an important distinction when solar radiation or high air velocities are involved.

Manikin response has been "calibrated" against human response where heat balance and discomfort sensations are concerned. However, the risk of cold-related muscular injury has not been studied as a function of sectional heat loss, as experiments designed to provoke such a response are generally regarded as unethical. An important future application of thermal manikins will be in epidemiologic studies of work situations in which people have already suffered cold-related muscular injury. Once sectional heat loss has been calibrated in this way, it will be possible to set both health and safety limits on thermal asymmetry, as well as comfort limits.

The development of thermal manikin techniques, as opposed to their application, is likely to continue, but will be a minority preoccupation in comparison. Reference has already been made to future developments of sweat simulation and of physical indices predicting manikin response in specific circumstances. Computer programs will probably be developed to model the physiological processes of heat storage and internal heat transfer, processes that are not usually simulated at present. It may be appropriate to develop computer programs that will simulate vasoconstriction by adjusting set values for skin temperature to achieve a target total heat loss under conditions of cold. This application would take some time but would provide a good estimate of resulting hand skin temperature in situations where it would be critical for skilled performance. Off-line estimates of heat loss with different skin temperature distributions can already be made more accurately if sectional clo values have been measured empirically. These program developments do not require any hardware changes and can be implemented very easily in the TORE and VOLTMAN systems.

The thermal assessment of complex environments is incomplete without some measurement of how the microclimate at the head affects the eyes. Dry, or even sweating, heat loss from the head itself is not an adequate measure. In the future thermal manikins for vehicle assessment may be provided with some additional sensors at the eye, and the response of these sensors will be related to human criteria of the kind developed by Wyon & Wyon (17).

For the special purpose of measuring human heat balance in survival and diving suits in water, robust

and water-resistant versions of existing manikins are required, but this application does not require any new principles of measurement. As human trials are, in this case, both unpleasant and dangerous, it would appear to be an ideal field of application for thermal manikin techniques. Manikins 3 and 4 of table 1 are already used for this purpose.

Availability of thermal manikins

Thermal manikins are not yet in series production. The potential market does not seem to justify the expense and practical difficulty of setting up series production. Each manikin system listed in table 1 was the result of a research project by researchers who would much rather use the equipment than make it. Familiarity with the equipment was thereby enhanced, a considerable advantage when malfunctions must be dealt with. Thermal manikin systems are complex, vulnerable and expensive, but they are cost-effective in a very wide range of applications. Research organizations wishing to acquire their own system are recommended to assemble the team of engineers and scientists who are to use it and then to make it possible for the team to build their own. An important provision is that they should do so in close collaboration with specialists who have already built a successful thermal manikin system. Between two and four person-months of specialist time is sufficient, and two person-years is a reasonable estimate of the total work involved. This approach has already been funded as a United Nations Industrial Development Organization project for technology transfer and was carried to a successful conclusion (18).

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