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Direct Measurement of the Thermal Responses of Nude Resting Men in Dry Environments*

DUNCAN MITCHELL**, C. H. WYNDHAM, A. R. ATKINS, A. J. VERMEULEN, H. S. HOFMEYR, N. B. STRYDOM, and T. HODGSON

Human Sciences Laboratory and Physical Sciences Laboratory, Chamber of Mines of South Africa, Johannesburg; National Mechanical Engineering Research Institute, Pretoria; and Department of Agricultural Technical Services, Pretoria, South Africa

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Summary. Two nude resting men were exposed for two-hour periods to each of 25 dry environments, with air temperatures ranging between 12.8° C and 49.1° C and wind speeds between 0.67 m/sec and 4.94 m/sec. The mean radiant temperature of the surroundings was kept equal to the air temperature. Rates of radiant and convective heat exchange were measured directly, separately and continuously. The men had reached a thermal steady state after 105 min in the warm environments, but not in the cold environments. Graphs are presented to show the effect of ambient temperature and wind speed on the radiation and convection rates attained after 105 min, as well as on metabolic rate, sweat evaporation rate, rectal temperature and mean skin temperature. These graphs revealed some important aspects of the behaviour of man's thermal control system. In particular the physiological conductance increased with increasing ambient temperature and then "saturated" at an ambient temperature near 35° C. This saturation resulted in a constant difference between rectal temperature and mean skin temperature irrespective of the environmental conditions.

Key-Words: Thermal Exchanges — Heat Balance — Thermoregulation — Responses to Heat and Cold.

Schlüsselwörter: Wärmeaustausch — Wärmeausgleich — Wärmeregulierung — Hitze- und Kältereaktionen.

To predict the physiological reactions of men working or living in particular thermal environments one must know first what the thermal stress on the body is and secondly how the parameters of physiological strain are related to thermal stress. The thermal stress is determined by the metabolic heat generation and the heat exchange with the environment. The relationship between stress and strain is determined by the mode of action of the thermoregulatory system.

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** Doctoral candidate in the Physics Department, University of the Witwatersrand, Johannesburg.

Many indices of heat stress and models of the thermoregulatory system have been proposed, but their confirmation and further development has been seriously limited by a lack of accurate quantitative information on human heat exchange [29]. Much valuable information can be obtained by exposing men to a systematically varied range of environments.

Classic studies of this kind were first performed in the 1930's [5, 13]. However, only recently has instrumentation become available for accurate environmental control and for the direct measurement of heat exchange. In the climatic chamber at the Human Sciences Laboratory of the Chamber of Mines a man in a typical working posture can be exposed to a 3 m by 3 m air stream which is very uniform in temperature and velocity distribution. Air temperature and humidity, wind speed and mean radiant temperature can be closely controlled over a wide range of values [8, 9]. Recently instrumentation has been developed for the climatic chamber by means of which the total radiation and convection from a man can be measured directly, separately and continuously [3, 16, 17].

This paper presents the results of a study in which two nude resting men were exposed to dry environments in which the air temperature was varied in five steps between 12.8° C and 49.0° C, and wind speed in five steps between 0.67 m/sec and 4.94 m/sec. Mean radiant temperature was kept equal to air temperature throughout. These results show the effect of environmental conditions, within this range, on the heat exchanges of the human body: metabolism, convection, radiation and evaporation; as well as on rectal temperature and mean skin temperature.

The results also reveal some interesting aspects of the behaviour of man's thermoregulatory system. When a man changes his environment or state of work his body at first tends to accumulate or lose heat, and its temperature rises or falls. This temperature change activates the metabolic, circulatory or sweating thermoregulatory systems to compensate the thermal stress and the rate of heat accumulation or loss is reduced completely or partially [5, 6, 18, 23]. When the rate of heat storage becomes negligible the man is said to be in a thermal "steady state". In the steady state, therefore,

$$q_M + q_C + q_R + q_E = 0$$

where q_M, q_C, q_R, q_E are the rates of heat loss (kcal/hr) by metabolism, convection, radiation and evaporation respectively. To test for the achievement of the steady state one can plot q_E against $-(q_M + q_C + q_R)$. A straight line through the origin should result. Alternatively one can divide the expression $(q_M + q_R + q_C + q_E)$ by the average specific heat of the body, giving the rate of change of mean body temperature. This shouls be zero in the steady state. When a man reaches a thermal steady state his body, therefore, is compensating exactly for the thermal load or drain imposed on it by the environmental conditions and the exothermic metabolic processes.

Methods

Subjects

Two adult men acted as subjects. Their physical characteristics are shown in Table 1. The weights are averages over the duration of the experiment. The radiant surface areas were measured in the photodermoplanimeter [10] in the posture adopted during the experiment. The total surface areas were calculated using the finding that the measured radiant surface area in the spread-eagle position represents $95^0/_0$ of the total surface area [7]. The men were highly acclimatized to heat by a programme of work in a hot humid environment. Their state of acclimatization was maintained artificially throughout the experiment.

Environments

The range of environmental temperature and wind speeds is shown in Table 2. The six wall panels of the climatic chamber, each of which can be thermostatically controlled, were maintained at air temperature. Each subject was exposed in turn to each of the five wind speeds at each of the five temperature conditions. Fifty experimental runs were therefore performed. Dry-bulb temperature stayed within 0.3° C of the set value over the ten runs at each condition, and wind speed within one per cent.

Measurements

Measurements of the radiant and convective heat exchange between the subject and his environment were made continuously by means of the 4-π radiometer [16, 17] and the convective heat exchange grids [3]. These have an accuracy of about five per cent. of the measured value. The evaporative heat exchange was determined by multiplying the subject's weight loss by the latent heat of vaporization of water at the prevailing mean skin temperature. The man was weighed using an electronic load cell balance with an accuracy of 15 g, and the weight loss was corrected for water consumed and urine voided. These measurements do not separate the heat exchanged in the respiratory tract from that exchanged at the skin surface.

Metabolic heat production was calculated from oxygen consumption. Expired air was collected periodically in a Douglas bag, and analysed with a paramagnetic oxygen analyser. The mean respiratory quotient for all the determinations during a particular run was used to determine the calorific value of the oxygen consumed [4].

Various physiological parameters were also determined. Heart rate was recorded periodically on an electrocardiograph. Rectal temperature was recorded continuously with an indwelling thermocouple probe containing four junctions of equal resistance connected in parallel. The junctions were positioned 5, 6, 7 and 8 cm from the sphincter.

Skin temperature was measured by means of a copperconstantan thermocouple. The subject was isolated in the climatic chamber and so had to measure his own temperature. Although radiometric measurement of skin temperature is undoubtably a more accurate method [27], a radiometer is not yet available with which a man can rapidly scan many sites around his own body. The thermocouple probe was designed to minimise the errors which normally occur in the thermoelectric measurement of skin temperature [21]. The wire was thin (30 AWG) and butt-soldered to give a small junction. The thermocouple was stretched across a bow-shaped holder. The wires lay in contact with the skin for at least 3 cm on either side of the junction to reduce heat conduction along the leads. The bow-shaped holder was attached to a springoperated tension gauge, so that the thermocouple was always applied to the skin with a force of 50 gm. The thermocouple assembly was calibrated (to 0.05° C) in a water bath against a substandard thermometer under the conditions and at the location of its subsequent use. The weighted mean skin temperature ($\overline{T}_s$) was calculated using measurements at twelve sites and a system of weighting coefficients based on the method of HARDY and DU BOIS [12].

Procedure

The subject arrived at the laboratory about one hour after eating either breakfast or lunch. He rested nude for a further hour in a neutral environment. Towards the end of the hour measurements were made of the oxygen consumption and body temperatures. The subject then entered the climatic chamber and mounted a bicycle ergometer. The first measurements of radiation, convection and body temperature were made within two minutes of his entering.

For each run the subjects remained in the climatic chamber for two hours, except for the runs at the two highest wind speeds in the coldest condition (set A), where they were withdrawn after one hour.

Water was taken *ad libitum* from a Dewar flask.

Results

The observations of each day's run were plotted graphically as a function of time of exposure. Smooth curves were fitted by hand to the plots of convection, radiation, skin temperature, rectal temperature and metabolic rate. The values of evaporative heat loss were plotted with step changes at the times of weighing. All subsequent results were extracted from these graphs, so that they were smoothed values taken from curves rather than observed values at given instants. A typical experimental record is given in Fig. 1.

Attainment of Thermal Balance

Fig. 2 shows a test for the existence of steady state conditions after 105 min of exposure. The points plotted are rates of change of mean body temperature calculated calorimetrically by dividing the net rate of heat loss ($q_M + q_C + q_R + q_E$) by the body mass and its specific heat, assumed to be 0.83 kcal kg^{-1} deg C^{-1} [2]. The rate at which mean body temperature was changing after 105 min of exposure is plotted against the rate of change after 5 min. It is clear that in warm environments (that is, those in which body temperature initially rises) control of the body temperature occurred in such a way that by the 105th min the rate of change of mean body temperature was small or zero. The steady state was attained. In cold environments the increased metabolism did not compensate the heat loss by convection and radiation completely, even after 105 min.

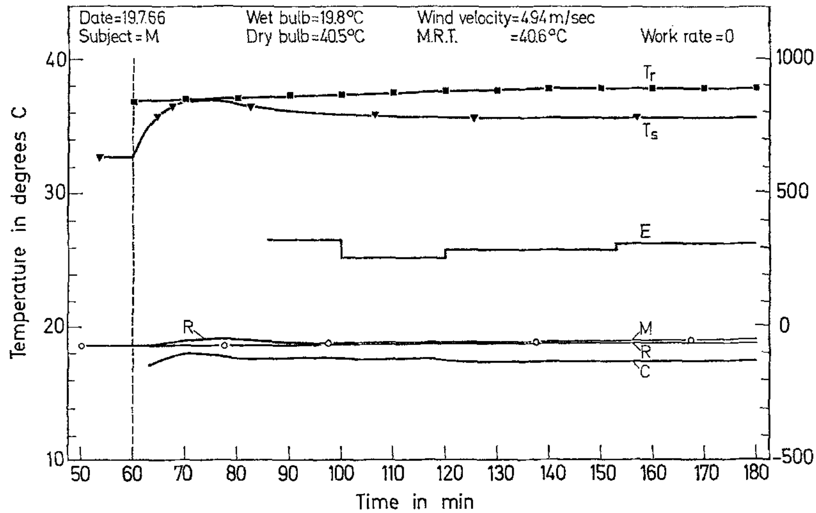


Fig. 1. Typical record of experimental result

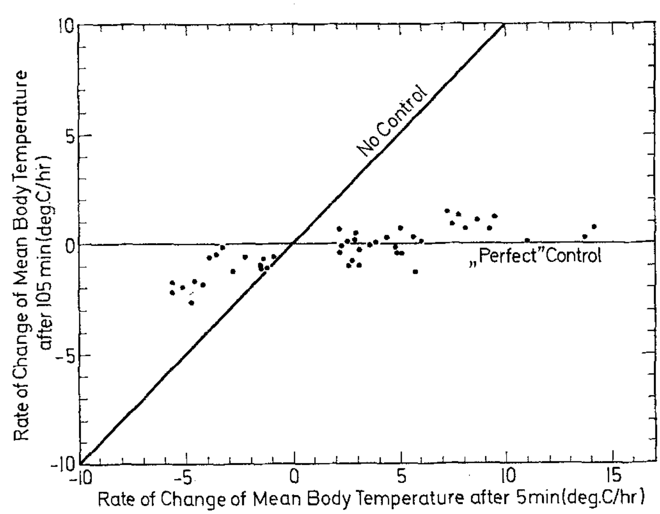


Fig. 2. Rate of change of mean body temperature calculated calorimetrically after 5 and 105 min of exposure

Fig. 3 shows the evaporative heat loss rate (q_E) plotted against the net heat gain ($-q_M - q_C - q_R$) after 105 min. The experimental points are scattered about the balance line, again showing that a thermal steady state had been attained. Fig. 4 is a similar scatter diagram after 60 min of exposure. The points corresponding to the higher sweat rates (and therefore to the hotter environments) tend to be scattered equally

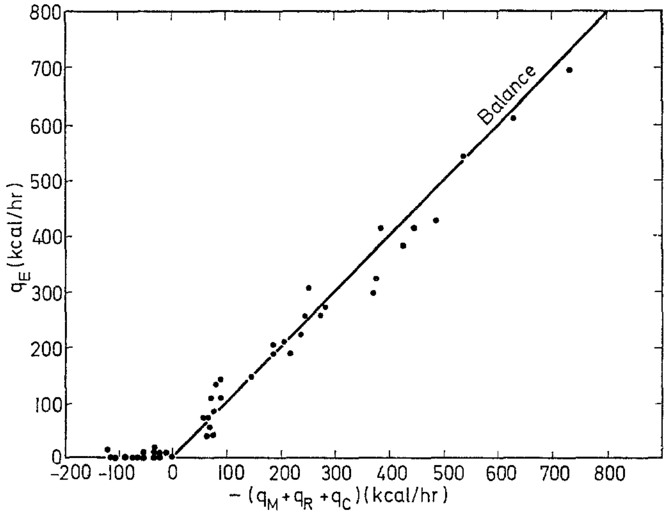


Fig. 3. Rate of evaporative heat loss versus net rate of heat gain after 105 min exposure

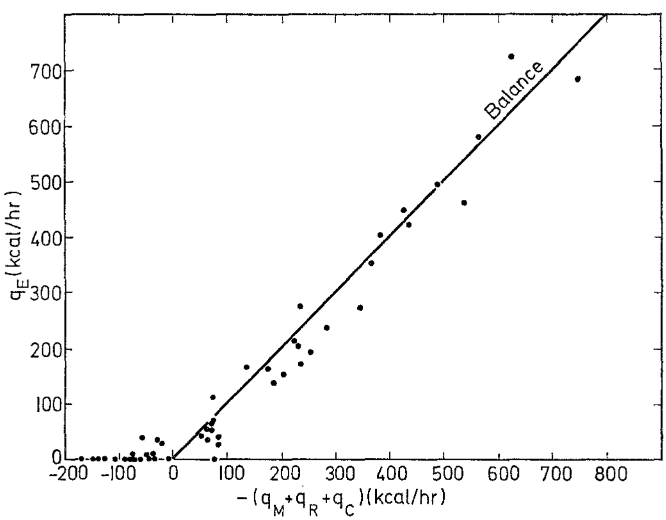
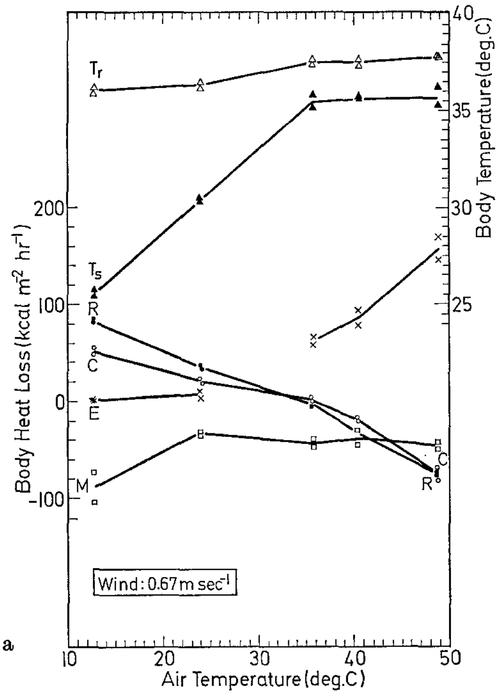


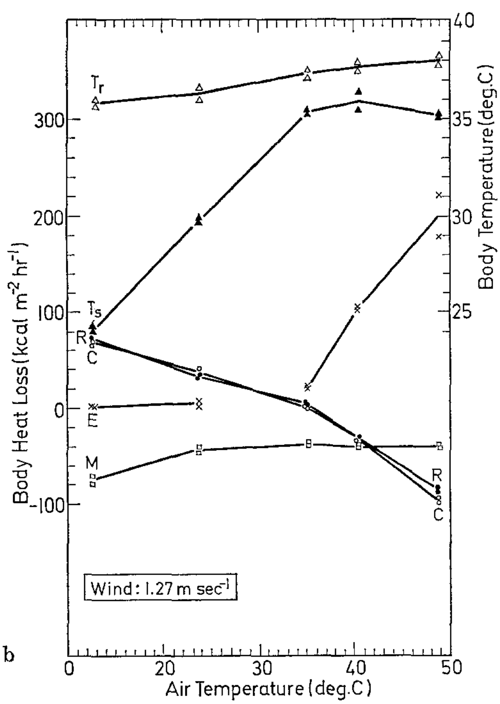
Fig. 4. Rate of evaporative heat loss versus net rate of heat gain after 60 min exposure

above and below the balance line, while those points corresponding to the lower sweat rates generally lie below the balance line. The response time of the human thermoregulatory system is longer in mildly stressful environments [20], and even though sweating occurred, a steady state was apparently not attained in one hour.



Tr
Ts
R
C
E
M
C
R
Wind: 0.67 m sec⁻¹
Body Heat Loss (kcal m⁻² hr⁻¹)
Body Temperature (deg. C)
Air Temperature (deg. C)
200
100
0
-100
40
35
30
25
10
20
30
40
50

Fig. 5a



Tr
Ts
R
C
E
M
R
C
Wind: 1.27 m sec⁻¹
Body Heat Loss (kcal m⁻² hr⁻¹)
Body Temperature (deg. C)
Air Temperature (deg. C)
300
200
100
0
-100
40
35
30
25
0
20
30
40
50

Fig. 5b

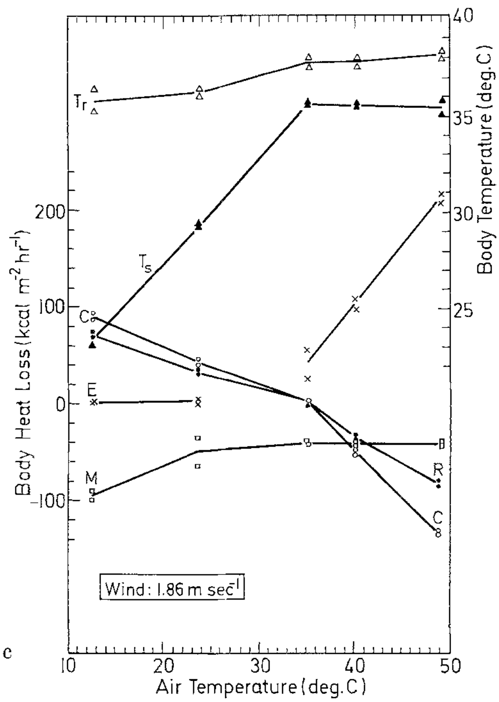

Tr
Ts
C
R
E
M
Wind: 1.86 m sec⁻¹
Body Heat Loss (kcal m⁻² hr⁻¹)
Body Temperature (deg. C)
Air Temperature (deg. C)
200
100
0
-100
40
35
30
25
10
20
30
40
50

Fig. 5c

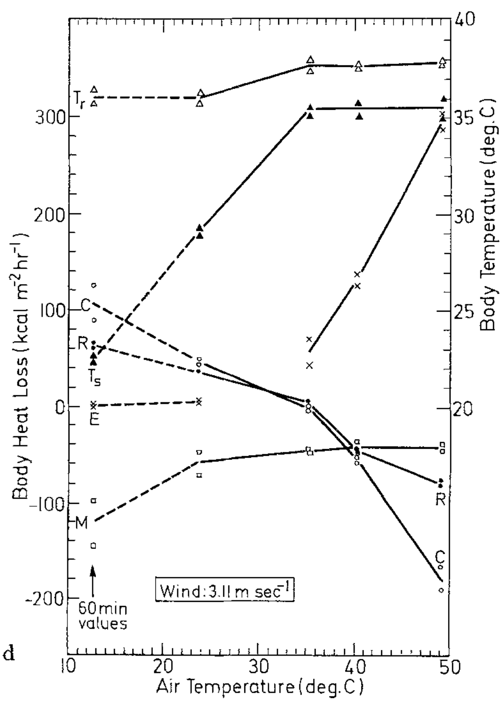

Tr
Ts
C
R
E
M
Wind: 3.11 m sec⁻¹
60 min values
Body Heat Loss (kcal m⁻² hr⁻¹)
Body Temperature (deg. C)
Air Temperature (deg. C)
300
200
100
0
-100
-200
40
35
30
25
20
10
20
30
40
50

Fig. 5d

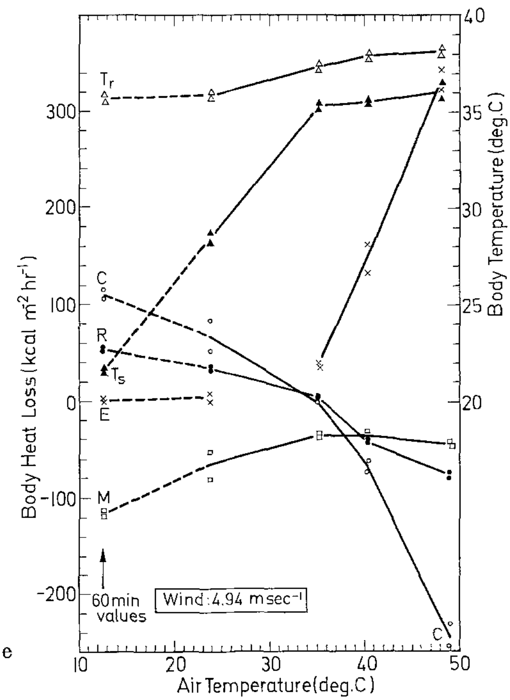


Fig. 5e

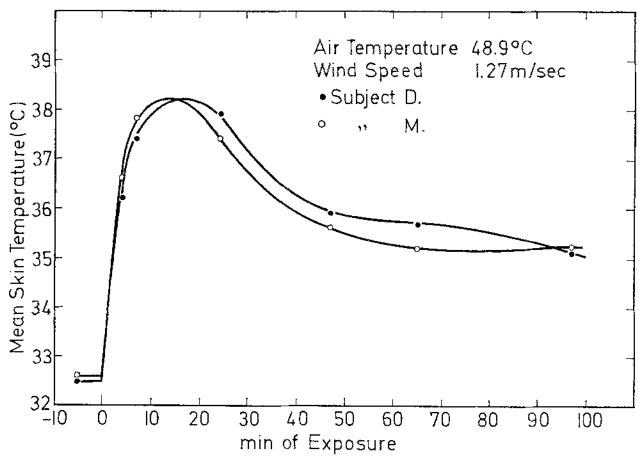
Fig. 5a—e. Thermal exchanges and body temperatures as functions of air temperature at five different wind speeds

Thermal Responses to Different Environments

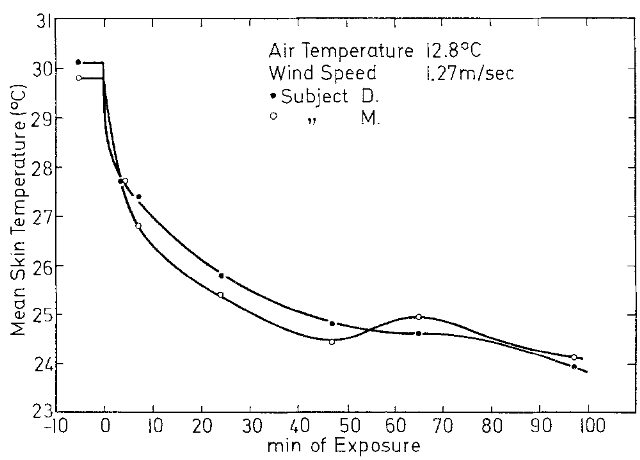
Fig. 5 shows values of radiant heat exchange, convective heat exchange, metabolic rate, evaporative heat loss and body temperature for the two subjects in the various environments. The radiation, convection and metabolic rate appeared constant during the last 30 min of exposure, and this constant value was plotted. For the reasons stated above, these values can be taken as corresponding to a thermal steady state in the warm environments but not in the cold environments. Where the values of the other parameters were still changing after two hours, the value prevailing at 105 min was used. At the two conditions under which the subjects were withdrawn after one hour, the values of all parameters at one hour were taken. These are distinguished in the figures. The figure shows the various parameters plotted as functions of air temperature at each of five wind speeds. The rates of heat exchange were expressed per unit of body surface area. This area was taken to be the total body area except in the case of radiation, where the radiant surface area (Table 1) was used.

Table 1. *Physical characteristics of subjects*

Subject	Weight (kg)	Height (cm)	Total surface area (m^2)	Radiant surface area (m^2)
D	62.2	165.5	2.02	1.63
M	53.9	166.2	1.88	1.53



a



b

Fig. 6a and b. Response of mean skin temperature on entering (a) a hot environment and (b) a cold environment

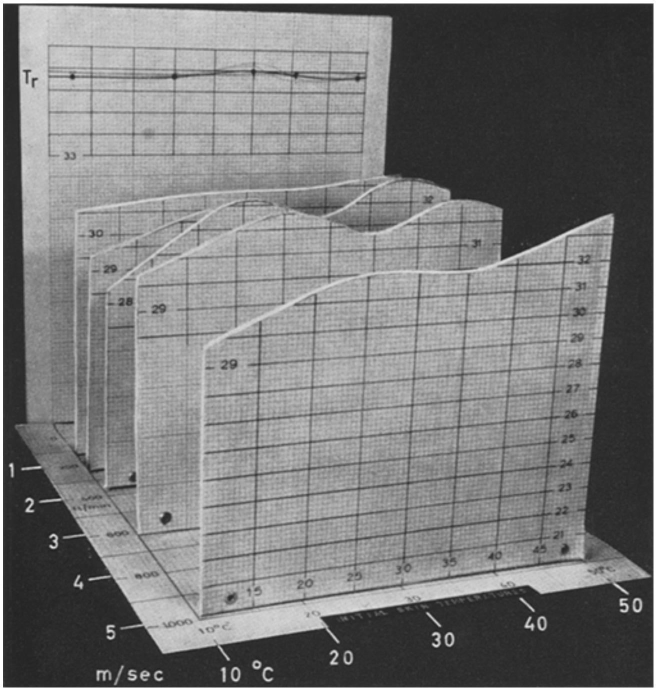

Tr
33
30
32
29
31
28
29
32
31
30
29
28
27
26
25
24
23
22
21
15
20
25
30
35
40
45
1
2
3
4
5
m/sec
10 °C
20
30
40
50
INITIAL SKIN TEMPERATURES

Fig. 7 a

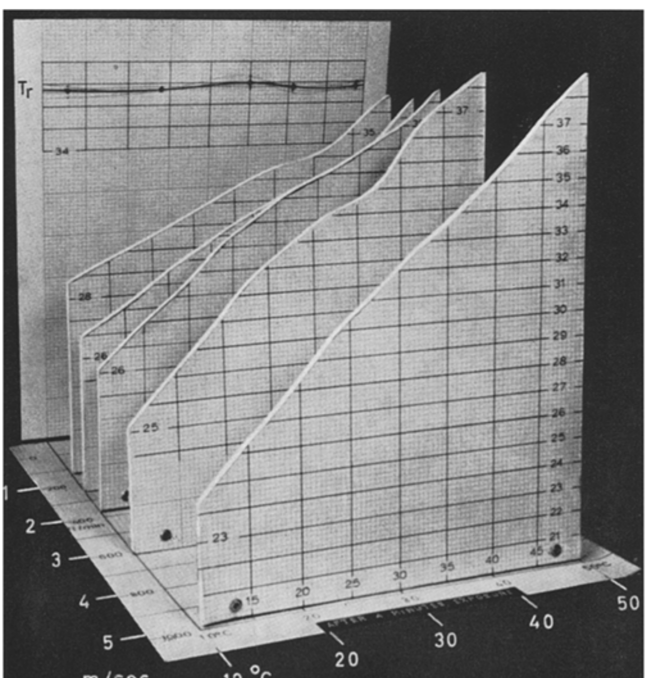

Tr
34
35
37
28
26
26
25
23
37
36
35
34
33
32
31
30
29
28
27
26
25
24
23
22
21
15
20
25
30
35
40
45
1
2
3
4
5
m/sec
10 °C
20
30
40
50

Fig. 7 b

Fig. 7 c

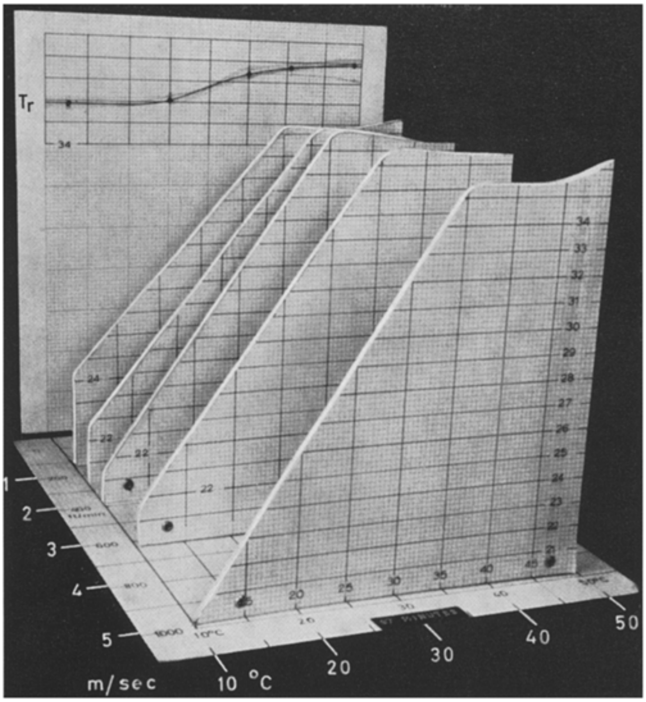


Fig. 7a—c. Mean skin temperature as a function of air temperature and wind speed (a) before exposure (b) after 4 min exposure (c) after 97 min exposure

Skin Temperature Response

The pattern of heat exchange between the subject and the environment divides naturally into two parts at the critical condition where the sensible heat exchange (radiation and convection) becomes a heat gain to the body rather than a heat loss. This critical condition occurred at an air temperature close to 35° C in this experiment. Below this critical temperature mean skin temperature decreased linearly with air temperature, while above it mean skin temperature was virtually independent of air temperature.

The typical pattern of skin temperature response to hot and cold environments is shown in Fig. 6, which represents the responses to temperatures of 48.9° C and 12.8° C at a wind speed of 1.27 m/sec. The response to hot environments ($\pm$ 40° C and $\pm$ 49° C) was characterized by a rapid rise in temperature in the first ten minutes, followed by a more gradual fall. A steady value was reached after about an hour. Overshoot was evident at all wind speeds. During exposures of the subject to the less hot environments at 35.3° C, his skin temperature rose gradually to a steady value without showing overshoot. When a subject entered a cold environment, his skin temperature fell rapidly at first and then more gradually. In the ± 24° C environments the skin temperature tended to reach a steady value after about an hour. In the ± 13° C environments, the temperature was still falling after 100 min of exposure.

The combined effects of air temperature, wind speed and time of exposure on the skin temperature response are shown in Fig. 7 which depicts photographs of three-dimensional graphs plotted with skin temperature along the y-axis, wind speed along the z-axis and air temperature along the x-axis. Each graph represents the mean skin temperature response at a different time of exposure: immediately before entering the climatic chamber (7a), after 4 min (7b) and after 97 min (7c). The mean values for the two subjects were plotted throughout. The rectal temperature at each ambient temperature is also shown behind the plots of skin temperature. Rectal temperature was affected only slightly by wind speed, so the average rectal temperature over all wind speeds was plotted for each air temperature.

The surface temperature response exhibited by the human body in the first few minutes after a change of environment was simply that of a physical body with no active thermal control (Fig. 7b). The mean surface temperature was linearly dependent on air temperature, the rate of change of skin temperature with air temperature increasing with increasing wind speed, presumably because of the increased convective heat exchange. In the hot environments, mean skin temperature sometimes rose to more than a degree higher than the prevailing rectal temperature.

After 97 min of exposure a clear pattern of skin temperature response was evident (Fig. 7c). Below a critical ambient temperature near 35° C the mean skin temperature was linearly dependent on ambient temperature. The rate at which skin temperature decreased with ambient temperature became greater as the wind speed became greater. At air temperatures above this critical temperature the mean skin temperature was virtually independent of both ambient temperature and wind speed. For all the environments studied with air temperatures lying between 35° C and 50° C, mean skin temperature always lay between 35.3° C and 36° C.

Discussion

Accuracy of Thermal Control

Fig. 2, 3 and 4 present some of the results of this study in a way which demonstrates the quality of man's thermoregulatory system. Any tendency for the body temperature to rise or fall induces a response to prevent any further rise or fall. Control of temperature is better achieved by sweating in the heat than by metabolic increase in the cold. A linear regression equation was fitted to the positive data of Fig. 3:

$$y = 13 + 0.929\,x.$$

The slope of the line had, therefore, approached to about 93% of that corresponding to perfect balance. Although this slope was not significantly different from unity, it is possible, however, that the calculated values of the evaporative heat loss rate (q_E) were slightly too low. The evaporative heat loss was calculated by multiplying the man's weight loss by the heat of vaporization of water at the prevailing skin temperature. There are two reasons why this multiplication factor could be higher. First, Hardy has suggested that evaporating sweat draws from the body not only the heat required to transform the water into the vapour phase but also the heat required to bring the resulting vapour into equilibrium with the water vapour in the surrounding air [11]. Second, the heat required to vaporize water from a sweat solution must be higher than that required to vaporize pure water [1]. If either of these additional factors were applicable the regression line would have had a slope closer to unity.

Effect of Environmental Conditions on Heat Exchange

Fig. 5 shows the responses of nude men sitting in a range of thermal environments wide in both air temperature and wind speed. To the best of our knowledge these results contain the first direct, separate measurements of the radiant and convective heat exchange of the human body.

The heat exchange by radiation and convection behaves according to the physical laws of heat transfer. The rate of heat exchange along these two paths is determined in the case of convection by the temperature difference between the surface of the body and the air and also by the wind speed, and in the case of radiation by the temperature difference between the body surface and the walls of the chamber. The sensible heat transfer in a particular environment depends, therefore, not only on the physical parameters of the environment but also on the skin temperature response in that environment.

Radiant exchange was only affected by wind speed because skin temperature was affected. Convection always increased with wind speed. In this study, where air and wall temperatures were equal, radiation and convection were equally important at a wind speed close to 1.27 m/sec (Fig. 5b). At higher wind speeds convection contributed the greater part to the sensible exchange. Wind speeds in everyday living conditions are generally much lower than 1.27 m/sec and thus radiation forms the bigger constituent, a fact not always taken into account by air-conditioning engineers. The large convective heat gain at high wind speeds when the air temperature exceeds 35° C is well demonstrated.

Above the critical ambient temperature, evaporation becomes the only available mechanism of body heat loss. It increased rapidly with air temperature at high temperatures, to compensate increasing convective heat gain. The evaporative heat loss curve is broken in Fig. 5 between ambient temperatures of 23.9° C and 35.3° C. In this region sweating began to increase rapidly. One cannot say exactly at what ambient temperature this increase began on the basis of these results. It seems reasonable that strong sweating will begin when the metabolism plus the net heat exchanges by all other methods becomes a heat gain to the body. The figure also shows the now well-known active thermoregulatory control in cold conditions brought about by the mechanism of increased metabolism [19]. This increase was evident at the 12.8° C exposure for all wind speeds, and at the 23.9° C exposure at the higher wind speeds.

Pseudo-saturation of the Conductance

Fig. 5 also shows an important interrelationship between rectal and skin temperature in the steady state in hot environments. In environments with temperatures between 35° C and 50° C, rectal temperature and skin temperature were separated by a constant gap of just over 2° C. A constant gap between rectal temperature and core temperature with varying ambient temperature is also evident in recent results from the JOHN B. PIERCE Foundation Laboratory [28]. The constancy of this difference apparently arises from the "saturation" of the mechanism of vasomotor control [14]. Heat generated in the body core is carried to the periphery primarily by means of the circulatory system. The overall facility with which the circulation transports heat may be described quantitatively by the "physiological conductance" [15], the net rate of heat transfer divided by the temperature difference driving the heat flow:

$$K = (M + S)/(T_c - T_s).$$

T_c is the core temperature, which is related quite well to the rectal temperature in the steady state. It is clear from this equation that if the metabolic rate M is constant, if the storage S is negligible and if the temperature difference $(T_c - T_s)$ maintains a constant value over a range of environments, then the conductance K must also remain constant. In the present experiment in the hot environments metabolic rate remained very constant at about 40 kcal m^{-2} hr^{-1}. The storage was very small after two hours (Fig. 2, 3). The constant difference between rectal temperature and skin temperature implies that the conductance, and therefore the state of the circulatory system, remained constant over a range of environments.

The thermoregulatory system of the body will attempt to increase the conductance in hot environments by increasing blood flow to the periphery, in order to facilitate heat dissipation from the body core. However, this improvement cannot be unlimited, and eventually the vasomotor mechanism saturates and the conductance adopts a constant value. These data give a value of about 20 to 25 kcal m^{-2} hr^{-1} deg C^{-1} for the maximum conductance of the resting subjects, which is in good agreement with the measurements of ROBINSON [26], and is much less than upper limit of about 100 kcal m^{-2} hr^{-1} deg C^{-1} imposed by the nonvascular outer layers of the skin, estimated to be 2 mm thick by HATCH [14]. The value is much lower than those known to be reached in working men [24,33]. However, the physiological conductance can increase in two ways in response to a demand. First, the proportion of the blood flow directed to the periphery can be increased by dilatation of the peripheral vessels and constriction of the non-peripheral vessels. Second, the cardiac output can increase. There is evidence that the increase in metabolic rate due to physical work is a more important stimulus to the heart to increase its output than vasodilatation of peripheral blood vessels due to heat stress [30,32]. If, then, the cardiac output does not increase appreciably in response to a thermal stress, the vasomotor control system will exhibit an apparent saturation corresponding to maximum dilatation of the peripheral blood vessels. Consequently, conductance can appear to saturate with increasing thermal stress in resting men at values much lower than those attained in working men.

Skin Temperature Response

The thermal stress imposed on a man by the environment depends on a number of easily measurable environmental variables (air temperature, wind speed, etc.) and on one physiological parameter: the mean skin temperature. As HATCH [14] has pointed out, a satisfactory heat stress index should be directly calculable from environmental parameters and measures of activity only. This therefore requires prediction of the mean skin temperature.

The virtual constancy of mean skin temperature in environments in which the sensible heat transfer constituted a heat gain to the body was apparently the combined result of thermoregulatory control of the body core temperature and pseudosaturation of the conductance. The evaporative control mechanism stabilized body core temperature in such a way that rectal temperature increased only slightly with ambient temperature (Fig.4). If core temperature and skin temperature were locked together by a constant conductance, as described above, then skin temperature necessarily could vary only slightly with ambient temperature.

We do not claim that mean skin temperature will remain independent of environmental temperature as the latter is increased beyond our limit of 50° C. Eventually the thermoregulatory system of the body will no longer be adequate and skin temperature, and all other body temperatures, will inevitably rise. Also, in humid environments where evaporation is not as effective in stabilizing body temperatures, this "plateau" in skin temperature response is probably reduced or absent.

That mean skin temperature was apparently independent of air temperature at high air temperatures was noticed, but not believed, by VERNON and WARNER as long ago as 1932 [31]. In their classical studies GAGGE [5] and HARDY [13] both showed a levelling-off of skin temperature under ambient temperatures of 35° C and higher. PHELPS and VOLD [24] claimed that mean skin temperature increased 0.25° C per degree C rise in air temperature. NEUROTH [22], who made a systematic investigation of environments between 5° C and 50° C, found that skin temperature increased with air temperature. STOLWIJK and HARDY [28] also came to that conclusion. In the exposures to higher temperatures an initial overshoot in mean skin temperature was noticed: the mean skin temperature after four minutes exposure was occasionally 3° C higher than its steady state value. STOLWIJK and HARDY [28] did not record this overshoot in a recent study in which the environmental temperatures were comparable to those used in this study. The explanation probably lies in the fact that the single wind speed which they used was lower than the lowest used in this study. Any proposed model of the thermoregulatory system must be able to account for this overshoot.

The linear relationship between mean skin temperature and air temperature in cold environments confirms the similar findings of IAMPIETRO [18]. IAMPIETRO deduced that, for air temperatures below 31° C, the change in mean skin temperature per degree Celsius change in air temperature was given by

$$\frac{1.066\,t + 57.1}{t + 70.7} - \frac{4.10}{V + 6.79}$$

where t is the length of exposure in minutes, and V the wind speed in m/sec. Our measured values of this parameter show good agreement with IAMPIETRO's formula ($r = 0.84$, $P < 0.001$). However, the values obtained in this study tended to be a little higher.

The two subjects used were of similar build (Table 1). The difference in temperature response in the cold between fat and thin men were therefore not clearly manifest here. The rate at which skin temperature decreases with decreasing ambient temperature in the cold will probably show large individual differences when men of different body composition are studied.

Table 2. *Environmental conditions*

Set	Temperatures (deg C)			Wind speed
	Dry bulb	Wet bulb	Mean radiant	(m/sec)
A	12.8	6.7	12.8	0.67
B	23.9	13.3	23.9	1.27
C	35.3	17.8	35.1	1.81
D	40.4	19.7	40.6	3.11
E	49.1	23.2	49.0	4.94

Conclusion

In conclusion, attention must be drawn to the fact that this study was carried out in simple artificial environments. Naturally occuring environments are very much more complex than those set up in this experiment. Only by a series of experiments in which not only air temperature and wind speed are varied but also humidity, radiant temperature and work rate, can a complete picture of man's thermal responses be obtained. Only then will one be able to make realistic predictions of how a particular man in a particular job will react to his environment. The complexity of the data on which these predictions must be based probably makes the use of a computerized system essential.

References

1. Blase, B., T. Morimoto, and R. E. Johnson: The viscosity and density of human eccrine sweat. Fed. Proc. **26**, 445 (1967) (Abstract only).
2. Burton, A. C., and O. G. Edholm: Man in a cold environment, pp. 41—42. London: Edward Arnold Publishers Ltd. 1955.
3. Carroll, D. P., and J. Visser: Direct measurements of convective heat loss from human subject. Rev. Sci. Instrum. **37**, 1174—1180 (1966).
4. Documenta Geigy: Scientific Tables, p. 628. K. Diem (Editor), Sixth Edition. Basle: J. R. Geigy S.A., 1962.
5. Gagge, A. P., L. P. Herrington, and C.-E. A. Winslow: Thermal interchanges between the human body and its atmospheric environment. Amer. J. Hyg. **26**, 84—102 (1937).
6. Glaser, E. M., and P. S. B. Newling: The control of body temperature in thermal balance. J. Physiol. (Lond.) **137**, 1—11 (1957).
7. Graan, C. H. van, and C. H. Wyndham: Body surface area in human beings. Nature (Lond.) **204**, 998 (1964).
8. Grant, W. L.: The design and development of a climatic chamber for the study of human reactions under different environmental conditions. J. S. Afr. Inst. Mech. Engnrs. **4**, 133—206 (1954).
9. — The performance characteristics of the climatic chamber of the chamber of mines applied physiology laboratory. S. Afr. Mech. Engnr. **7**, 109—157 (1956).
10. Halliday, E. C., and T. J. Hugo: The photodermoplanimeter. J. appl. Physiol. **18**, 1285—1289 (1963).

11. HARDY, J. D.: Heat transfer. In: Physiology of temperature regulation and the science of clothing (L. H. NEWBURGH, Ed.). Philadelphia: W. B. Saunders Co. 1949.
12. —, and E. F. DU BOIS: The technic of measuring radiation and convection. J. Nutr. **15**, 461—475 (1938).
13. —, and G. F. SODERSTROM: Heat loss from the nude body and peripheral blood flow at temperatures of 22° C to 35° C. J. Nutr. **16**, 493—510 (1938).
14. HATCH, T.: Assessment of heat stress. In: Temperature its measurement and control in science and industry (C. M. HERZFELD Editor-in-Chief), Vol. 3, Part 3, Biology and Medicine (J. D. HARDY, Ed.). New York: Reinhold Publishing Corporation 1963.
15. HERRINGTON, L. P., C.-E. A. WINSLOW, and A. P. GAGGE: The relative influence of radiation and convection upon vasomotor temperature regulation. Amer. J. Physiol. **120**, 133—143 (1937).
16. HODGSON, T.: Climatic chamber and instrumentation for heat transfer studies on man. Proc. XVth International Congress on Occupational Health, pp. 553 to 557 (1966).
17. —, and C. H. WYNDHAM: Recent developments in measuring techniques for the study of heat transfer in man. Report MEG 458, Council for Scientific and Industrial Research, Pretoria, South Africa, 1966.
18. IAMPIETRO, P. F.: Prediction of skin temperature of men in the cold. J. appl. Physiol. **16**, 405—408 (1961).
19. — J. A. VAUGHAN, R. F. GOLDMAN, M. B. KREIDER, F. MASUCCI, and D. E. BASS: Heat production from shivering. J. appl. Physiol. **15**, 632—634 (1960).
20. MACDONALD, D. K. C., and C. H. WYNDHAM: Heat transfer in man. J. appl. Physiol. **3**, 342—363 (1950).
21. MOLNAR, G. W., and J. C. ROSENBAUM: Surface temperature measurement with thermocouples. In: Temperature its measurement and control in science and industry (C. M. HERZFELD, Editor-in-Chief), Vol. 3, Part 3, Biology and Medicine (J. D. HARDY, Ed.). New York: Reinhold Publishing Corporation 1963.
22. NEUROTH, G.: Die Hauttemperatur im Dienste der Wärmeregulation. Pflügers Arch. ges. Physiol. **250**, 396—413 (1948).
23. NIELSEN, B.: Regulation of body temperature and heat dissipation at different levels of energy and heat production in man. Acta physiol. scand. **68**, 215—227 (1966).
24. PHELPS, E. B., and A. VOLD: Studies on ventilation. 1. Skin temperature as related to atmospheric temperature and humidity. Am. J. publ. Hlth **24**, 959—970 (1934).
25. ROBINSON, S.: Physiological adjustments to heat. In: Physiology of heat regulation and the science of clothing (L. H. NEWBURGH, Ed.). Philadelphia: W. B. Saunders Co. 1949.
26. — Circulatory adjustments of men in hot environments. In: Temperature its measurement and control in science and industry (C. M. HERZFELD, Editor-in-Chief), Vol. 3, Part 3, Biology and Medicine (J. D. HARDY, Ed.). New York: Reinhold Publishing Corporation 1963.
27. STOLL, A. M.: Techniques and uses of skin temperature measurements. Ann. N. Y. Acad. Sci. **121**, 49—56 (1964).
28. STOLWIJK, J. A. J., and J. D. HARDY: Partitional calorimetric studies of responses of man to thermal transients. J. appl. Physiol. **21**, 967—977 (1966).
29. — — Temperature regulation in man—a theoretical study. Pflügers Arch. ges. Physiol. **291**, 129—162 (1966).

30. Taylor, H. L., Yang Wang, L. Rowell, and G. Blomqvist: The standardization and interpretation of submaximal and maximal tests of working capacity. Pediatrics **32**, 703—722 (1963).
31. Vernon, H. M., and C. G. Warner: The influence of the humidity of the air on capacity for work at high temperatures. J. Hyg. (Lond.) **32**, 431—463 (1932).
32. Williams, C. G., C. H. Wyndham, G. A. G. Bredell, N. B. Strydom, J. F. Morrison, and J. Peter: Circulatory and metabolic reactions to work in heat. J. appl. Physiol. **17**, 625—638 (1962).
33. Wyndham, C. H.: Role of skin and of core temperature in man's temperature regulation. J. appl. Physiol. **20**, 31—36 (1965).

Dr. C. H. Wyndham
Director, Human Sciences Laboratory
Chamber of Mines
P. O. Box 809
Johannesburg/South Africa