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Calculation of mean body temperature[1]

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Four young male subjects were exposed for 1 h to environmental temperatures of 8.5 °C, 14.0 °C, and 20.0 °C while lying on a rope mesh cot. During exposure they wore swimming trunks only. Heat production, skin temperature at seven locations, and rectal temperature were measured. Mean body temperatures (MBT) and heat debts were calculated from Burton's equations and also from equations determining radiative, convective, and evaporative heat losses. It was found that a linear equation with constant coefficients, such as Burton's, for measuring MBT does not allow for the fact that in the non-steady state the body continues to lose heat even though the skin temperature is relatively constant. During the initial period of cold exposure the coefficient of skin temperature when calculating MBT should be much smaller than at later stages in the cooling.

Introduction

Various formulas have been proposed as a means of calculating the mean body temperature (MBT) of human beings. Burton (1) proposed that under steady conditions the MBT of an individual could be estimated by the following relationship:

$$\mathrm{MBT} = 0.67T_r + 0.33\ \mathrm{MST}$$

where T_r is the rectal temperature and MST is the mean weighted skin temperature. Burton's subjects were exposed to an environmental temperature of 23.3 °C, on a canvas bed. Burton and Bazett (2) calculated MBT when the subjects were immersed in a water bath so that MST was quite stable. The relation obtained was:

$$\mathrm{MBT} = 0.65T_r + 0.35\ \mathrm{MST}.$$

Hardy and DuBois (3) calculated in their experiments that the equation would be:

$$\mathrm{MBT} = 0.80T_r + 0.20\ \mathrm{MST}.$$

Their subjects lay nude on a sheet-covered cot in a calorimeter at temperatures from 22 to 35 °C. In almost every case there was some loss of body heat and the subjects sometimes shivered. In a later series of experiments (4, 5) on women they proposed a series of equations at various temperatures:

$$\mathrm{MBT} = 0.60T_r + 0.40\ \mathrm{MST\ at\ 22–25\ °C}$$
$$\mathrm{MBT} = 0.70T_r + 0.30\ \mathrm{MST\ at\ 25–28\ °C}$$
$$\mathrm{MBT} = 0.80T_r + 0.20\ \mathrm{MST\ at\ 28–30\ °C}$$
$$\text{and } \mathrm{MBT} = 0.90T_r + 0.10\ \mathrm{MST\ at\ 33–36\ °C}.$$

The experimental data of Burton and Bazett and Hardy and DuBois were obtained under stable conditions; in the experiments of Hardy *et al.* (3–5), measurements were made after 3 h exposure to the environmental temperatures.

The above type of equation has been applied to the analysis of the cooling of subjects acutely exposed to cold, e.g. in calculation of heat debt (6). Since in experiments of this kind subjects are not likely to be in a steady state, it is possible that the coefficients will change not only with environmental temperature but also with time of exposure.

To investigate this possibility, four subjects were exposed to various environmental temperatures for 1 h and their rectal and skin temperatures and heat production measured. The total heat loss by radiation, convection, and evaporation was calculated and from this, together with heat production, the change in body heat content could be determined, i.e. heat debt. Changes in MBT were then calculated from the heat debt and mean specific heat of the body, and the coefficients of T_r and MST in a linear equation of the type used by Burton were calculated to determine their dependence upon environmental temperature and time of exposure.

Methods

Four young male subjects were exposed for 1 h to environmental temperatures of 8.5 °C, 14.0 °C, and 20.0 °C, during the weeks of September 26, October 3, and October 10, 1965 respectively. During exposure they lay on a rope mesh cot and wore swimming trunks only.

Mean skin, rectal, and room temperatures were obtained in a manner similar to that of Hurley *et al.* (6). The percentage of oxygen in expired air was measured by

PD-2940

[1]DRML Research Paper No. 668.

means of a gas-phase oxygen transducer (model GP10, Chemtronics Inc.), and the minute respiratory volumes (V_E) were determined with a pneumotachometer consisting of a metal screen with a differential pressure transducer to determine the drop of pressure across the screen. The outputs of the transducers were recorded on an Offner dynagraph. Heat production was calculated from percentage oxygen in the expired air and V_E, by Weir's method (7). Ambient air movement was determined with a Kata thermometer. Control readings were taken for 20 min previous to exposure, with the subject wrapped in blankets.

Mean body temperatures and heat debts were calculated at 5-min intervals by Burton's equations, i.e.

$$MBT_c = 0.67T_r + 0.33\,MST,$$

$$\text{Heat debt } (D_c) = \frac{0.83 \times \text{body weight (kg)} \times \Delta MBT_c}{\text{surface area (m}^2)} \quad \text{kcal/m}^2$$

where 0.83 = specific heat of body tissue in kilocalories per kilogram per degree Centigrade (6). The change per minute in mean body temperature during the exposure period was determined directly from heat production and heat loss measurements, as follows:

$$\Delta MBT_e = \frac{(H_p - H_L)\,(\text{surface area (m}^2))}{\text{weight (kg)} \times 0.83}$$

where H_p = heat production (Weir's method), and H_L = the sum of radiative, convective, and evaporative losses, i.e.

$$H_L \sim K_1(T_s^4 - T_a^4)A + K_2(T_s - T_a)A + (K_3 V_E + 0.17)\ \text{kcal/m}^2 \text{ per min},$$

where K_1 = Stefan–Boltzmann constant, i.e. 8.1×10^{-10} kcal/m² per degree⁴ per min,
T_s = mean skin temperature (°K),
T_a = ambient air temperature (°K),
A = effective radiating surface of the body = 78% of the surface area (8),
K_2 = 0.0515 kcal/m² per min per °C for air movement of 0.06 m/s (9),
0.17 kcal/m² per min = minimal heat lost by evaporation, and
K_3 is additional heat lost by evaporation due to an increase in environmental temperature. This varies for each environment (10).

Since the emissivity of human skin and that of the environment are approximately unity, omitting these terms from the radiation equation does not produce a significant error. The total heat loss by radiation, convection, and evaporation was calculated for each 5-min interval. The corresponding heat debt (D_e) was determined as the cumulative algebraic sum of heat production and total heat loss in the same interval.

Since initially the subjects were under blankets and in a resting comfortable state so that conditions resembled those of Burton, the initial MBT was arbitrarily chosen at $MBT_0 = 0.67T_r + 0.33$ MST. From this value and ΔMBT_e, based on heat debt, values were calculated for the coefficients of Burton's equation in the form

$$MBT_0 - \Delta MBT_e = (1 - x)T_r + x\,MST.$$

Similarly, calculated heat debt values, D_c calculated from rectal and skin temperatures by Burton's equations, were compared with experimental values, D_e obtained from measurements of heat production and loss.

Results and Discussion

It is observed in Fig. 1 that at 8.5 °C the cumulative heat debt D_c calculated from T_r and MST overestimates the experimental value D_e based on heat production and heat losses.

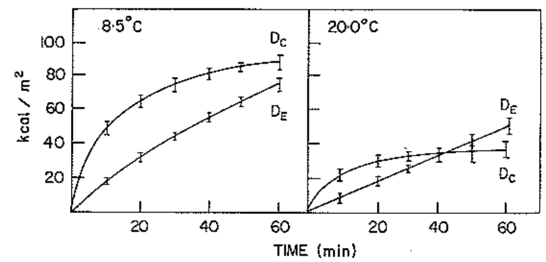

FIG. 1. Cumulative heat debt, where heat debt is radiative loss + convective loss + evaporative loss − heat production, and heat debt calculation is obtained from ($\Delta MBT_c \times 0.83 \times$ weight)/area.

At 20.0 °C the initial portion of the curves follows the same trend as that at 8.5 °C, but at the end of the hour D_e is greater than D_c. It can also be seen that the cumulative debt D_c increases rapidly during the first 10 to 20 min and then appears to approach a constant value, where the cumulative debt D_e increases continuously and almost linearly during the entire experimental interval.

It is evident from Fig. 1 that with the onset of cooling, D_c overestimates D_e, and consequently ΔMBT_e is less than ΔMBT_c. The coefficient of skin temperature in Burton's equation should therefore be less in the early stages of cooling. The variation of both coefficients with time and environmental temperature in the non-steady state is shown in Fig. 2. A rapid decrease in the MST coefficient is required to accommodate the initially rapid cooling of the skin (see Fig. 3). Over an extended interval of time the body then continues to lose heat while rectal and skin temperatures remain essentially constant. Thus heat is lost from the shell, the temperature gradient becoming shallower as a greater depth of tissue is cooled. Although MST decreases more slowly, the mean shell temperature continues to fall, and the MST coefficient steadily increases as the fraction of cooled shell increases (see Fig. 2). Measurement of temperature gradients beneath the skin would assist in developing and applying this concept.

When using Burton's equation for MBT it must be remembered that the weightings used are for temperature values and not for mass, i.e.

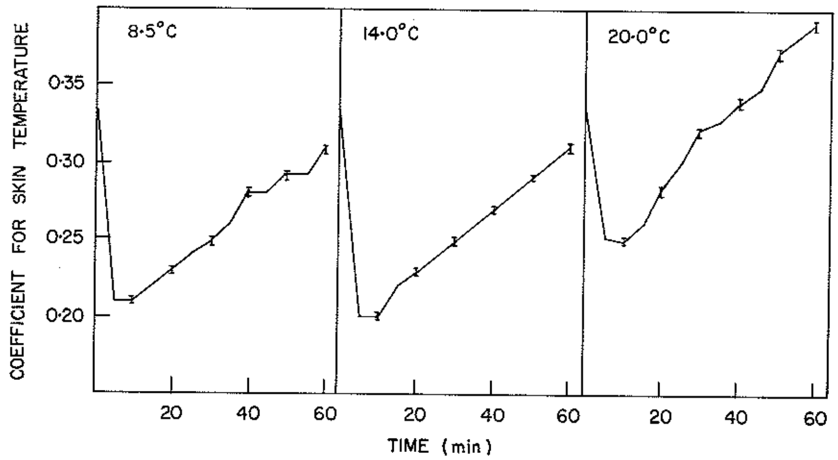

FIG. 2. Calculation of mean skin temperature coefficient using MBT $= (1 - x)T_r + x$ MST.

Burton does not imply that the body is 67% core and 33% shell; indeed he estimated that at least 54% of the body mass lies within 1 in. of the body surface and that core temperature is reached only at a depth of 1 in. or more (11).

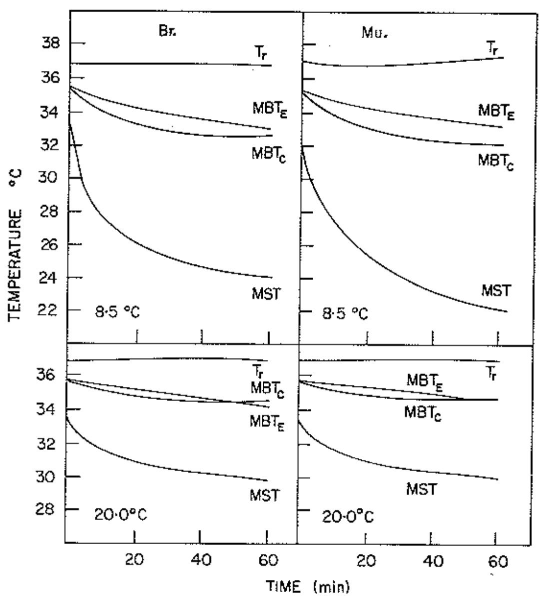

FIG. 3. Comparison of T_r, MST, MBT_e, and MBT_c for two subjects at 8.5 °C and 20.0 °C.

Hardy, Milhorat, and DuBois (4) found that, above 24 °C, good estimates of MBT could be made with either Burton's formula or their own, but below 24 °C a better estimate was obtained by a formula giving equal weight to rectal and skin temperatures. Their subjects, however, were exposed to these temperatures for 3 h. Our subjects were exposed for 1 h, but at the end of the hour the MST coefficients were rising (see Fig. 2) and it is possible that at the end of 3 h a new equilibrium would be reached giving a greater weight to skin temperature corresponding to a larger mass of cooled shell tissue. This is supported by the fact that at 20 °C the weightings after 1 h are approximately 0.60 for rectal and 0.40 for mean skin temperature.

Conclusion

From these results it is evident that the coefficients for rectal and mean skin temperatures in Burton's formula for mean body temperature vary with both time and ambient temperatures under non-steady state conditions, i.e. during an acute exposure of 1 h or less.

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