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Application of a heat budget model to study thermal stress during exercise*

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सार–प्रस्तुत शोधपत्र में व्यायाम की अवधि में मानव में उष्मा प्रतिबल की प्रागुक्ति के लिए विकसित यंग के ऊष्मा बजट निदर्श का व्यायाम की अधिकतम संस्तुत अवधि की परिवेश तापमान, आपेक्षिक आर्द्रता और विकिरण के साथ-साथ व्यायाम के स्तर के फलन के रूप में परिभाषा करने के लिए प्रयोग में लाया गया है । यह निदर्श शरीर में ऊष्मा के जनन, विसरण एवं भंडारण का लेखा-जोखा प्रस्तुत करता है और सौर विकिरण एवं वस्त्रों के प्रभाव को भी प्रदर्शित करता है । साथ ही किसी दिए हुए परिवेश की दशाओं में समय के फलन के रूप में त्वचा और क्रोड़ के तापमानों तथा निर्जलीकरण की प्रागुक्ति करता है ।

प्रस्तुत शोध पत्र में दिए गए व्यायाम की अधिकतम संस्तुत अवधि के चार्टों को उन क्रियाओं की व्याख्या करने के लिए काम में लाया जा सकता है, जो अपेक्षाकृत गर्म एवं आर्द्र जलवायु में कम हो जाती हैं। इन चार्टों के आधार पर भारत का जैविक मौसम विज्ञानी वर्गीकरण करके उन क्षेत्रों का निरूपण किया गया है, जहां मनुष्य को गर्मी और लू के दुष्प्रभाव से बचाते हुए अलग-अलग ऋतुओं में शारीरिक व्यायाम के विभिन्न स्तर निश्चित किए जा सकते हैं ।

ABSTRACT. In the present paper, a heat budget model developed by Young (1979) which predicts heat stress in humans during exercise is applied to define the maximum recommended duration of exercise (MRDE) as a function of ambient temperature, relative humidity, radiation as well as the level of exercise. The model accounts for the generation, dissipation and storage of heat in the body and allows for solar radiation and the effect of clothing, and predicts the skin and core temperatures and dehydration as a function of time under given ambient conditions.

The MRDE charts presented in the paper could be used as guides in defining the types of activities that should be restricted under relatively warm and humid climates. Based on these charts, a bio-meteorological classification of India is attempted to delineate regions where different levels of physical activity may be permitted in the different seasons, without exposing the human subjects to the risks of heat exhaustion and heat strokes.

1. Introduction

Thermal stress criteria in use at present are generally based on human comfort indices which attempt to relate temperature and humidity to subjective feelings of comfort. Most of these relate to persons clad in ordinary summer clothing and avoiding vigorous physical exercise. However, criteria which relate to exercising persons who are exposed to heat exhaustion and heat strokes are generally lacking eventhough the dangers of heat stress in exercising persons under conditions of warm temperatures and high humidities are well known.

Depending on the rate of work or exertion, the human body generates heat which is either stored internally or dissipated. Heat may be dissipated by conduction/convection from the skin, by evaporating sweat, by warming the inhaled air or by evaporation into the inhaled air. If heat is not dissipated, the internal (core) temperature rises. A core temperature of 40°C is considered to be the upper limit for safety in laboratory studies (Givoni and Sohar 1968) placing upper limits on the duration of exercise for healthy persons.

In the present paper, a heat budget model (young 1979) which predicts heat stress in humans during exercise is applied to determine the maximum recommended duration of exercise (MRDE) as a function of ambient temperature, relative humidity, radiation as well as level of exercise. The effect of clothing is also illustrated.

2. The heat budget model

The model of heat transfer in and from the human body is based on that described by Choisnel (1976). The model considers that heat is generated internally at a given rate and this heat may be lost by warming the inhaled air (C_R), by evaporating moisture into the inhaled air (E_R) or transfering the heat through the body to the surface (H_b). The surface of the body may gain heat by intercepting solar radiation, direct or diffuse (R), lose heat by evaporation from the moist skin (E) and transfer heat directly by conduction/convection from the skin (C). Radiative transfer of heat between the skin and the surroundings is neglected

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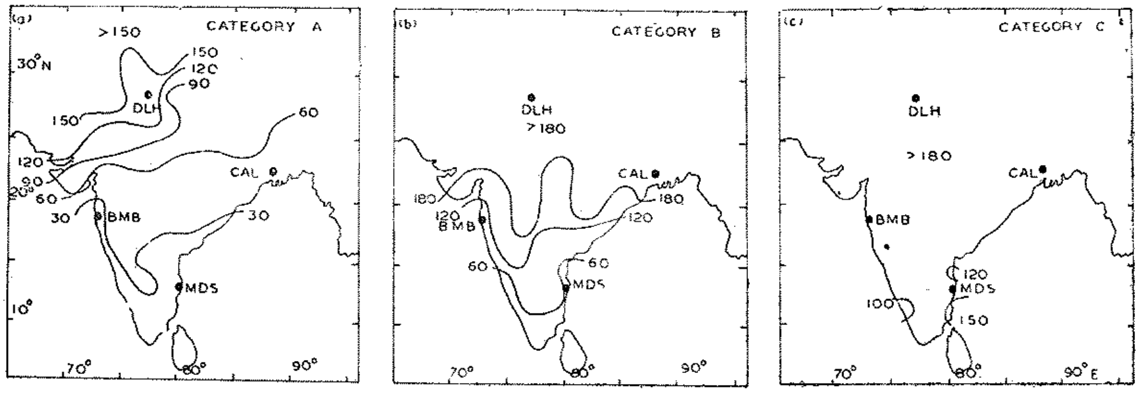
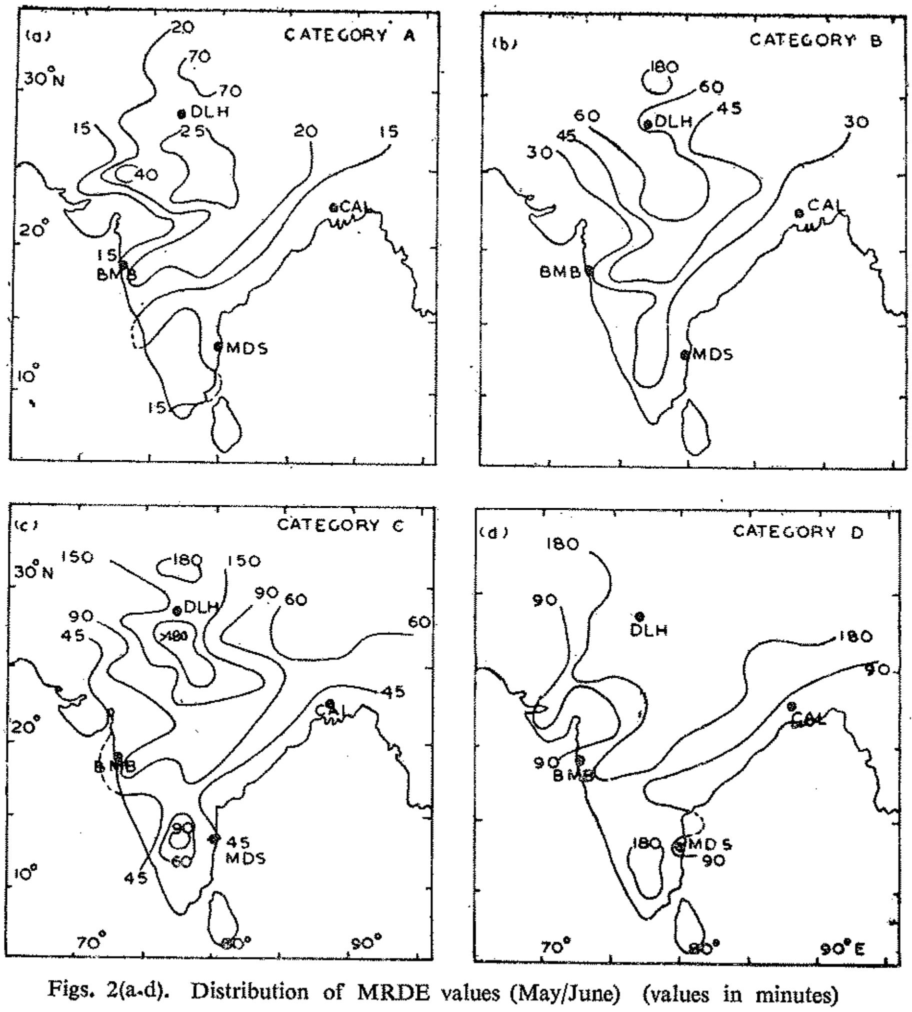


Figs. 1(a-c). Distribution of MRDE values (January) (values in minutes)



Figs. 2(a-d). Distribution of MRDE values (May/June) (values in minutes)

The solution of the terms H_b, C and E depend on knowing skin temperature (T_{sk}). Assuming that the change in heat stored in the surface layers is negligible the heat balance equation for the surface is :

$$H_b + R = C + E \tag{1}$$

Following Choisnel, H_b and C may be expressed as :

$$H_b = K_b\ (T_c - T_{sk}) \tag{2}$$

$$C = 104\ V^{0.6}\ (T_{sk} - T_{\infty}) \tag{3}$$

where K_b is the conductance of the body (cal m^{-2} °C^{-1}), T_c the core temperature, V the relative air speed (ms^{-1}) and T_{∞} the ambient air temperature. The evaporative cooling term (E) is a function of the ambient pressure, and the vapour density gradient between the skin surface and the ambient air. The solar radiation term (R) includes both direct and diffuse radiation and depends on the mean albedo and surface areas intercepting the radiation. The mean albedo is a weighted average which considers that the body is 65% covered with clothing with a variable albedo and remaining 35% is wet skin (albedo 0.5).

Solution of the heat balance Eqn. (1) is accomplished based on the above considerations and the skin temperature is calculated therefrom. The model assumes that approximately 20% of the energy resulting from the increased metabolic rate during exercise appears as mechanical work with the remaining 80% contributing to the generation of heat (Givoni and Sohar 1968). The rate at which heat is being generated (H_g) is given by :

$$H_g = 0.8\,H_{total} + 0.2\,H_{rest} \quad (4)$$

The total metabolic heat equivalent (H_{total}) is given below for various levels of exercise and the heat generation at rest (H_{rest}) is assumed to be 490 cal m^{-2} min^{-1} for an average person (*after* Young 1979) :

Level of exercise	*Type of activities*	*Total metabolic heat equivalent (cal m^{-2} min^{-1})*
A	running at 12 mi h^{-1}	12940
B	running at 10 mi h^{-1}	9800
C	running at 8.6 mi h^{-1} competitive bike racing	7980
D	jogging at 7.5 mi h^{-1} (cycling (13 mi h^{-1})	6620
E	jogging at 2.6 mi h^{-1} football tennis basket ball	5000
F	walking at 3 mi h^{-1} golf baseball	2060

The observations of Ekblom *et al.* (1970) that a 1% weight loss from sweating results in a 0.3°C rise in core temperature while the skin temperature remains constant, is interpreted here as a reduction in the conductance of the body with water loss. Based on these data :

$$K_b = 502 - 1720\ (1 - W/W_0) \quad (5)$$

where Wo and W are body weight initially and during exercise respectively. The initial body conductance is taken to be 502 cal m^{-2} min^{-1} $°C^{-1}$ at the onset of sweating.

The model predicts both skin and core temperature. Changes in skin temperature are assumed to affect 20% of the body mass and the core temperature is maintained by 80% of body mass.

3. Application of the model

Using this model, the human response to a wide variety of ambient conditions at various levels of exercise can be evaluated. A convenient manner for summarizing these is to present the maximum recommended duration of exercise (MRDE) as a function of temperature and humidity. The MRDE as defined here is the time required for the core temperature to reach 40°C from an initial value of 37°C. For healthy individuals the threshold core temperature of 40°C seems a reasonable constraint on exercise.

Climatological data from about 85 representative Indian stations which enjoy a variety of climates from per humid to arid has been used to determine the MRDE for various levels of exercises in the coldest (January) and warmest (May or June) months. Of these stations chosen 13 are in coastal regions, 7 are in elevations greater than 1000 m above sea level and the rest are in the plains. Isolines of MRDE have been drawn in an attempt to delineate regions where different levels of activity may be permitted for specified periods without exposing the human subjects to the risks of heat exhaustion or heat strokes. All the charts (Figs. 1-3) are based on the responses of a lightly clothed person with no solar radiation for exercise levels ranging from normal walking (category F) to Olympic calibre marathon running (category A).

4. Analysis and results

4.1. *MRDE in January (winter)*

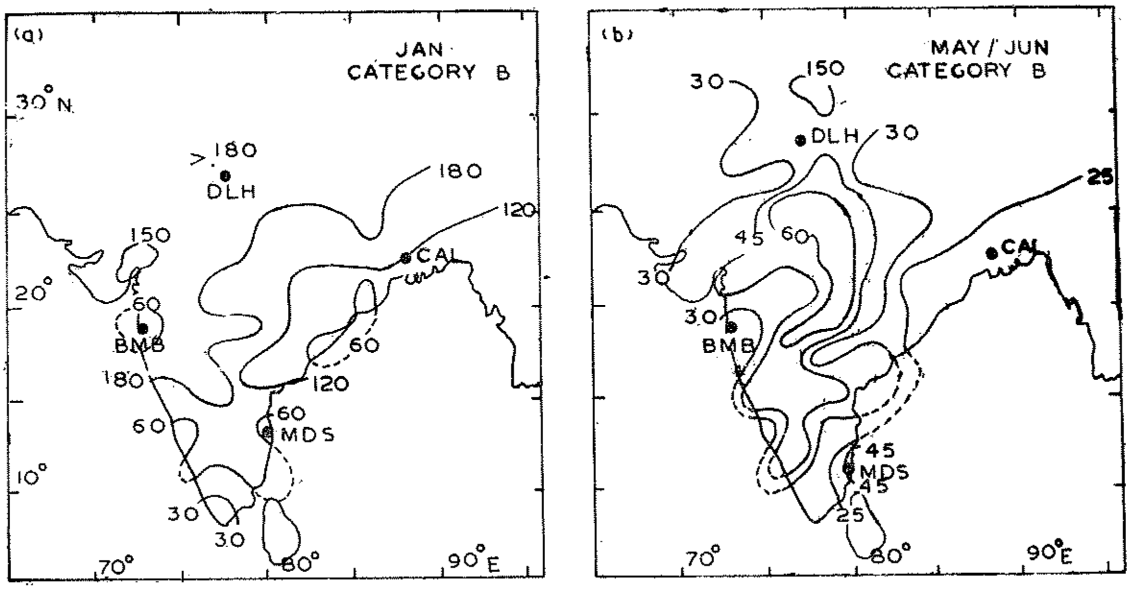
Figs. 1(a) to 1(c) show the distribution of MRDE for exercise levels A to C respectively. As expected the MRDE increase over all parts of the country as the level of exercise decreases from A to C. Charts for levels D, E and F have not been drawn as all regions have MRDE greater than 180 minutes.

The MRDE increases from Peninsular India to the northern parts of the subcontinent. Whereas a person could exercise at level A (*e.g.*, running at 12 mi h^{-1}) for more than 120 minutes at Delhi, he would encounter exhaustion within 30 minutes in the southern parts of Peninsular India. For exercises of level B (*e.g.*, running at 10 mi h^{-1}) the MRDE is greater than 180 minutes for almost all regions north of 20°N latitude. South Tamil Nadu and Kerala have MRDE values slightly lower than 60 minutes. For exercises of level C almost the entire country has MRDE greater than 180 minutes except three small pockets on Tamil Nadu and Kerala coasts.

4.2. *MRDE in May/June (Summer).*

Figs. 2(a) to 2(d) respectively depict the distribution of MRDE over India for exercise levels A to D in the warmest month (May/June). Charts for levels E and F have not been drawn as MRDE exceeds 180 minutes over all regions. These charts very clearly show that the higher summer temperatures have restricted the MRDE to values lower than in winter.

For exercise level A, a person would encounter heat exhaustion within 15 minutes in the southern, western and eastern parts of the country. Over central India this level of exercise would be safe upto 25 minutes. Only the hill stations in sub-Himalayan North India afford conditions for exercise upto 70 minutes.



Figs. 3 (a&b). Effect of clothing on MRDE (values in minutes)

For exercise level B, the MRDE is about 60 minutes in North India while it is less than 30 minutes throughout the coastal zone of the country and over extreme eastern India. Exercise level C could be continued upto 45 minutes in the coastal belt of Peninsular India while in the northern and central parts of the country, 150 minutes would be quite a safe period. A small region in the heart of the country has MRDE exceeding 180 minutes. A person could exercise at level D for more than 180 minutes over most parts of north and central India. Only over coastal Andhra, Orissa and West Bengal, heat exhaustion is likely to occur within 90 minutes. Over the rest of the country exercises could be for periods between 90 and 100 minutes. In general all hill stations with low mean temperatures have MRDE above 180 minutes in both summer and winter.

4.3. *Effects of radiation and clothing*

The results presented above assume night time conditions and that the effect of clothing is negligible, *i.e.*, the clothing is light and porous and does not significantly retard evaporation or the conduction of heat. However, a person may not always be properly clothed to maximise heat loss when doing exercise or work during day time. In such a case the amount of solar radiation absorbed is dependent on the type, colour and amount of clothing. Figs. 3(a) and 3(b) detail the MRDE for a person assumed to be wearing dark coloured clothing with an albedo of 20% and doing exercise of level B during day time with a solar radiation of 1L/min. It is seen that in January the MRDE is considerably reduced for regions in Peninsular India and the 180 minutes isochrone is shifted north (Fig. 3a). In May (Fig. 3b) too almost all the stations have lower MRDE compared to persons lightly clad (Fig. 2b). These results suggest that the inclusion of solar radiation in the model is equivalent to a temperature increase of about 2°C and that of wearing dark clothing can have the effects of the ambient temperatures upto 3°C.

4.4. *Use of the above charts*

The MRDE charts presented here are intended to be used as guides to determine the types of activities that should be restricted under warm and humid conditions. If a reasonable forecast of the expected temperature and humidity during the day is given one might limit the duration of activity below the MRDE or even suggest the activity itself should be avoided. For example, when the ambient temperature and humidity are 30°C and 50% respectively the MRDE is 60 minutes for category B level of exercise. Any type of activity of this level should be restricted to less than 60 minutes.

Factors such as aclimatization and pre-exercise hydration are not considered here. The MRDE presented apply only to healthy and trained individuals and should be regarded as upper limits to the duration of exercise or work.

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