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REVIEW

Heat stress and strain in exercise and sport

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Summary Heat stress arising from the thermal environment is of concern to sports medicine and to sports administration because of the perceived risk of heat casualties, in particular heat stroke. Many sports organizations recommend environmental indices such as the WBGT for assessing risk and setting environmental limits for training and competition. But the limits are not justified by evidence. This article describes the nature of heat stress in sport and how it may be assessed objectively. Heat stress and the principal human responses to exercise heat stress are reviewed briefly. Metabolic heat production and the thermal environment provoke separate and largely independent physiological strains. Metabolic heat production drives body core temperature, and the thermal environment drives skin temperature; the combined stresses are integrated to drive sweat rate. Control of core temperature depends on adequate sweat production and the capacity of the environment to evaporate the sweat. The nature of exercise heat stress is demonstrated by rational analysis of the physical heat exchanges between the body and the environment. The principles of this analysis are applied to critical review of current practice in the assessment of heat stress in sport. The article concludes with discussion of research to establish methods for objective sport-specific assessment of heat stress.

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Introduction

Heat stress arising from the thermal environment is of concern to sports medicine and to sports administration because of the perceived risk of heat casualties. Guidelines intended to safeguard sports people from ill effects of heat stress often recommend environmental limits for sports participation, but do not provide objective evidence or justification for the limits. Such limits must be evidence-based; otherwise they could allow participation in potentially dangerous conditions. Alternatively, if they are too conservative, they could cause needless anxiety and restrict participation unnecessarily. Objective assessment of risk is essential in circumstances where commercial and organizational considerations restrict opportunities for rescheduling events to avoid adverse environmental conditions. Appropriate management of heat stress in sport therefore requires proper understanding of the stress and its likely impact on participants. The purpose of this article is to demonstrate the nature of heat stress in sport, and how it may be assessed objectively.

Heat stress and strain in sport are a complex mix of behaviour, physics and physiology. Nonetheless the thermal stresses arising from exercise and the environment can be analysed systematically to predict sweating requirements and determine environmental conditions in which body temperature cannot be controlled.

Behaviour underlies heat stress in sport because vigorous exercise imposes significant thermoregulatory stress which may be compounded by the thermal environment. Little can be done to change the environment, but in warm environments the athlete can adjust exercise heat production to achieve a tolerable overall stress.[1] By contrast, in laboratory investigations behavioural regulation is excluded because exercise intensity is controlled by the investigator. Furthermore the laboratory environment usually does not reproduce the air movement over the body created by high intensity free moving exercise.[2] Consequently, laboratory results may not always be appropriate to formulating guidelines for managing heat stress in the real world of sport.[3]

Exercise heat stress

Heat production

Heat production (H) arising from muscular activity is usually the main component of sports heat stress. Table 1 shows examples of heat production and the potential for thermoregulatory strain in sports. In sport exercise heat production is a function of maximal aerobic power and relative exercise intensity. Thus in football heat production is the product of players' moderate relative maximal aerobic power and exercise intensity, but large body mass. Whereas in endurance running it is a function of the athlete's high maximal aerobic power and very high exercise intensity; it is also entirely the product of individual motivation.

Heat is held in the body as a function of its mass, the mean specific heat of the body tissues, and its mean temperature. Change in body heat content results in change in body temperature (Appendix A). To maintain tolerable body temperature during exercise the metabolic heat load must be balanced by an equal transfer of heat from the body to the environment.

Heat transfer between the body and the environment occurs by heat flow down temperature and humidity gradients through three independently acting physical processes: thermal radiation, convection and evaporation. Generally, heat transfers facilitate overall heat loss, but heat may also be gained from the environment to add to the metabolic heat load, or environmental conditions may prevent adequate heat loss.

Table 1 Metabolic heat stress and potential for thermoregulatory strain in sport

	Tennis	Football	Running
Body mass (kg)	70.0	95.0	65.0
$\dot{V}_{O_2\ max}$ ($LO_2\ min^{-1}$)	4.2	5.2	4.9
Exercise intensity (%$\dot{V}_{O_2\ max}$)	60	75	85
Metabolic heat production (W)	880	1330	1410
Sweat evaporation required for heat balance ($L\,h^{-1}$)	1.3	2.0	2.1
Predicted steady state core temperature (°C)	38.4	39.2	39.7
Rise in core temperature with no heat loss (°C h^{-1})	9.4	14.5	22.5

Radiative heat transfer

Radiative heat transfer (R) is the transfer of heat between surfaces of different temperature. Radiative heat transfer between the environment and the body is described by the equation $R = k_r(T_{sk} - T_r)$, where k_r is a constant, T_{sk} the mean skin temperature and T_r is the mean radiant temperature (MRT) of the surroundings.[4] Radiative heat exchanges may include simultaneous losses to cooler surroundings and gains from warmer surroundings. The net radiant flux is represented by the MRT which can be assessed with a globe thermometer.[4–7]. In sunlight, the radiant heat load arises from direct, reflected and reradiated heat. In the six hours around midday the radiative heat loads from the sun acting on an exercising person range about 100—200 W.[8,9]

Convective heat transfer

Convective heat transfer (C) is a function of four factors. It is described by the equation: $C = k_c v^n (T_{sk} - T_a)$, where the constant k_c represents the thermal properties of air and the pattern of air flow over the body, v is the air velocity over the body surface, and T_{sk} and T_a are skin and air temperatures, respectively.[4] Fig. 1A shows that in air temperatures below about 35 °C skin temperature is higher than air temperature so that heat is lost by convection, but at higher air temperatures skin temperature is lower than air temperature and convection adds to the heat load. With vigorous exercise, even in cool conditions, heat losses by convection and radiation are usually not sufficient to achieve thermal balance and additional cooling by sweat evaporation (E) is required. The requirement for evaporative cooling (E_{req}) to maintain thermal balance is therefore one component of heat stress.

Requirement for evaporative cooling

The evaporative requirement (E_{req}) is determined by the sum of the metabolic heat production and the radiative and convective heat exchanges. To achieve thermal balance and control of body tem-

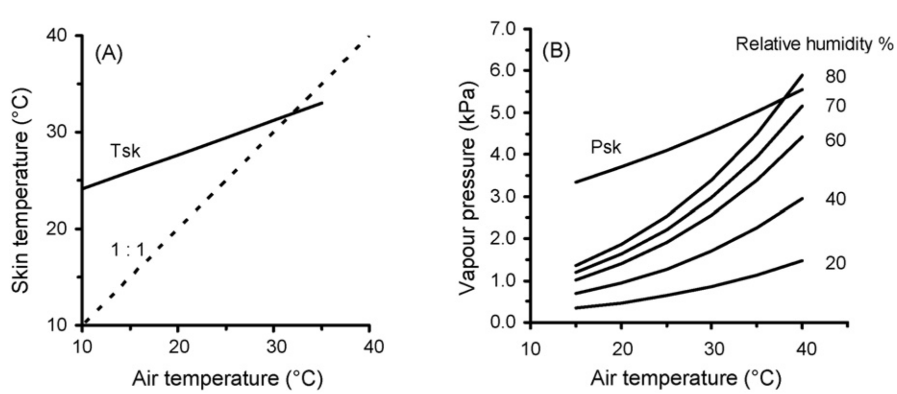

Figure 1 Relationships between skin temperature and air temperature (A), and absolute and relative humidities (B). (A) 1:1, skin temperature = air temperature. (A) The skin to air temperature difference determines the potential for convective heat exchange. (B) P_{sk} is the saturated vapour pressure at skin temperature. Vapour pressure indicates absolute water content of air. At a fixed relative humidity, e.g. 70%, vapour pressure varies with air temperature as the water holding capacity (saturated vapour pressure) varies with air temperature. P_{sk} varies with skin temperature. The skin to air vapour pressure gradient determines potential for evaporation of sweat.

perature the net heat load arising from $H \pm R \pm C$ must be balanced by evaporative cooling (E); thus, $E_{req} = H \pm R \pm C$. Clearly, E_{req} provides an estimate of sweat requirement, but to achieve thermal balance sufficient sweat must evaporate to meet E_{req}. Whether adequate evaporative cooling can be achieved depends on: (1) sufficient physiological sweat production and (2) whether the environment will allow sufficient evaporation.

Environmental evaporative capacity

The evaporative capacity of the environment (E_{max}) is thus the second component of heat stress. It is solely an environmental parameter and is the maximum rate of evaporation possible in the prevailing conditions. To achieve adequate evaporative cooling E_{max} must be at least as great as E_{req}. Sweat evaporation equals E_{req} unless E_{max} is lower than E_{req}, in this circumstance sweat evaporation is limited by, and equals, E_{max}. Evaporative cooling occurs as the result of vapourisation of water at the skin surface and the transfer of water vapour to the environment in a physical process similar to convective heat transfer.[4] The environmental evaporative capacity (E_{max}) is described by the equation: $k_e v^n (P_{sk} - P_a)$. The numerical value of the evaporative constant k_e is 15—16 times greater than the convective constant k_c[4]; P_{sk} and P_a are the water vapour pressures (absolute humidity) at the skin surface and the ambient air, respectively.[4] Vapour pressure is a measure of the absolute water content of the air. During active sweating the vapour pressure at the skin is assumed to be the saturated pressure at skin temperature. Thus, air flow over the skin (v), and absolute humidity, rather than relative humidity (RH%), determine sweat evaporation. The relationships of air temperature, relative humidity and water vapour pressure are shown in Fig. 1B. Clearly, at the same air temperature vapour pressure increases with increase in RH%. But at the same vapour pressure RH% decreases as air temperature increases because the vapour pressure represents a lower proportion of the saturated pressure. For example, Fig. 1B shows that the ambient vapour pressure 2.0 kPa is about 80% RH at 21 °C and 40% RH at 33 °C. Fig. 1B also shows that in warm humid conditions the ambient vapour pressure is high and hence the skin to ambient vapour pressure gradient, the potential for evaporation, is low. By contrast, in hot dry conditions the vapour pressure gradient, and thus the potential for evaporation, is high because the skin saturated vapour pressure is high and the ambient vapour pressure is low.

Index of heat stress

Clearly, E_{req} and E_{max} together incorporate all the components of thermal stress. Belding and Hatch suggested the ratio of E_{req} to E_{max}, as a rational and comprehensive index of heat stress: heat stress index (%) = $(E_{req}/E_{max})100$.[10] When E_{max} exceeds E_{req} (HSI < 100%) sweat evaporation can match E_{req}, and body temperature can be controlled. But if E_{req} exceeds E_{max} (HSI > 100%) sweat evaporation, and cooling, is limited to E_{max}. In this circumstance sweating continues, often at a higher rate than required to meet E_{req}, and the skin is dripping wet; but evaporative cooling is insufficient. Consequently, there is relative thermoregulatory failure. Heat is stored in the body, body temperature rises progressively and the heat stress cannot be tolerated indefinitely. The rate of heat storage (S), and thus the rate of rise of body temperature, is determined by the difference between the heat load indicated by E_{req} and the heat loss limited to E_{max}: $S = E_{req} - E_{max}$. See Appendix A.2 for calculation.

Clothing impacts on both E_{req} and E_{max}. By reducing air movement over the skin, and imposing a resistance to the flow of heat and water vapour through the fabric itself, it insulates the body from convective exchanges and restricts sweat evaporation. Clothing also acts as a screen against external radiant heat.

In summary, heat stress is a function of six independently acting factors: metabolic heat production, thermal radiation, air temperature and humidity, air movement over the body surface, and clothing. The physical basis and the assessment of heat stress are described in detail by Kerslake,[4] Santee and Gonzalez,[11] and Parsons,[12] and are summarized by Budd[6] and Brotherhood.[7]

Physiological responses to exercise heat stress

Physiological temperature regulation must respond more or less precisely to the net heat load (E_{req}) arising from the combined effects of exercise and the environment. For the purposes of describing and understanding the physical nature and effects of exercise heat stress the physiological responses of chief interest are skin temperature, sweat rate, and body core temperature.

Skin temperature (T_{sk}) is taken as the weighted average temperature of the body surface. It is important for its role in heat exchanges with the environment and in the control of sweating,[13,14] and also because of its effect on circulatory responses[15] and thermal sensation.[16] In light sports clothing skin temperature is largely independent of metabolic rate,[13,17] but varies widely with air temperature,[13,14,18–20] with a minor effect of humidity.[19] It is also influenced by air movement, and is lower in free moving exercise than at rest.[2,18–21] Fig. 1A shows the relationship of skin temperature to air temperature.[18,20] Solar radiation increases skin temperature by 1.5–2 °C.[8,18,22]

Sweat rate is associated independently with metabolic rate,[13,17,18,22] radiative heat exchange[8,9,18] and the components of convective heat exchange: air temperature and air movement.[13,14,18,21] Thus it effectively integrates the net heat load (E_{req}) arising from metabolism and the environment. Maximal sweat rates vary widely between individuals depending on factors such as age, maximal aerobic power and heat acclimatization.

Deep body (core) temperature (T_c) is of concern because a core temperature exceeding about 41.5 °C may lead to collapse and possibly heat stroke. In sport, rectal temperatures of 40–41 °C in endurance running[17,20,22,23] and 39.5 °C in the football codes[24–27] are normal responses to strenuous exercise. In moderate environments, following the onset of exercise sweat rate and core temperature increase for about 20 min and then plateau, indicating that sweat evaporation has achieved thermal balance.[13,21] The higher but controlled core temperature is not determined by absolute metabolic rate but is related to the athlete's exercise intensity expressed relative to their maximal aerobic power (%$\dot{V}_{O_2\,max}$).[17,28] Lind and others have demonstrated that in contrast to skin temperature, core temperature is controlled at the level determined by the intensity of exertion independent of a wide range of environmental conditions.[29–32] Lind termed the range of environmental conditions in which core temperature is independent of the environment the *Prescriptive Zone* (PZ), and demonstrated that the range of the PZ varies with metabolic heat production.[30] Sport-specific prescriptive zones are not yet known. Davies[20] showed that the PZ for running at 85% $\dot{V}_{O_2\,max}$ is very narrow. In air temperature 21 °C, RH 50%, and air velocity equal to running speed, thermal equilibrium was not achieved and rectal temperature rose progressively to 40 °C in 60 min.

In summary, thermoregulatory responses follow closely the thermal stresses arising from exercise and the environment. These relationships provide a rational basis for analysing and describing heat stress in terms of the physiological strain arising from the stress.[10,33] In exercise, metabolic heat production and the thermal environment provoke separate and largely independent physiological strains. Body core temperature is independent of the environment, but is driven by metabolic heat production in relation to individual maximal aerobic power. The environment drives skin temperature. The combined stresses are integrated to drive sweat rate. Provided the environment allows adequate physiological sweat production to evaporate thermal equilibrium and control of core temperature can be achieved.

The purpose of this article is to describe the nature of heat stress in laboratory exercise and sport. In laboratory exercise the subject is static and thermal stress can be studied by manipulating metabolic rate and the thermal environment. By contrast, exercise intensity in sports activities is self-selected. Moreover, vigorous activity creates air movement over the skin which modifies the athlete's thermal environment profoundly.[1,2,18]

Rational analysis of heat stress

The rational analysis of heat stress suggested by Belding and Hatch[10] was employed to generate examples of exercise and environmental heat stress for laboratory exercise and for free running. Rational analysis applies fundamental physical principles to estimate each of the avenues of heat exchange between the body and the environment. The analysis predicts sweat requirements and determines whether balance between heat load and heat loss can be achieved.

Methods

The effect on heat stress of varying environmental conditions was examined by analyzing heat stress in laboratory exercise. Heat stress in actual sport was demonstrated by analyzing heat stress in free running. Heat exchanges were estimated using equations recommended by Belding and Hatch[10,12]:

$$R = 5.5\,(T_{sk} - \mathrm{MRT})\,\mathrm{W\,m^{-2}} \tag{1}$$

$$C = 7.6v^{0.6}\,(T_{sk} - T_a)\,\mathrm{W\,m^{-2}} \tag{2}$$

$$E_{max} = 117v^{0.6}\,(P_{sk} - P_a)\,\mathrm{W\,m^{-2}} \tag{3}$$

where T_{sk} is the mean skin temperature (°C), MRT the mean radiant temperature (°C), v the air velocity over the body (m s^{-1}), T_a the air temperature (°C), P_{sk} the saturated vapour pressure at skin temperature (kPa), and P_a is the ambient vapour pressure (kPa). Heat transfer in Watts per square meter Du Bois body surface area.

These basic equations describe heat exchanges for a nude person. A clothing factor of 0.92 was applied to each equation for the effect of light athletic vest and shorts with an estimated insulation of 0.2 Clo.[12] By combining exercise heat production (H) and skin temperature with Eqs. (1)—(3) any combination of metabolic and environmental heat stress can be evaluated. Readers can readily gain a better understanding of heat stress by analysing their own sports scenarios. Worked examples are given in the Appendix A.1.

Eqs. (1)—(3) were used to examine the effects of varying environmental conditions on heat stress in the laboratory and for free running. Heat exchanges and E_{max} were calculated for a wide range of air temperatures, humidities, air velocities and running speeds for an individual with surface area 1.8 m^2. In the laboratory heat production was set at 800 W on a cycle ergometer. Air velocity was varied at 0.2 m s^{-1}, 0.5 m s^{-1}, and from 1 m s^{-1} to 6 m s^{-1} at 1 m s^{-1} intervals. For free running speeds were set at 12 (3.3), 14 (3.9), 16 (4.4) and 18 (5.0) km h^{-1} (m s^{-1}). Heat production was predicted from running velocity, and air velocity was taken as running speed so that metabolic heat production and air velocity were matched realistically. For both laboratory exercise and free running air temperature was varied from 10 °C to 40 °C at 5 °C intervals. Relative humidity was set at approximately 70% for each air temperature thus providing a range of vapour pressures (Fig. 1B). Mean radiant temperature for estimation of radiative heat exchange was taken as being equal to air temperature. Skin temperature in relation to air temperature was predicted by a regression equation derived from Adams[18] and Davies.[20] Graphs were constructed from the calculated data to illustrate the components of exercise heat stress in relation to the thermal environment.

Results

The purpose of the results given here is to demonstrate the nature of heat stress. Figs. 2—5 show the effects of varying environmental conditions in the laboratory on thermal stress for a fixed heat production of 800 W.

Fig. 2 illustrates convective heat exchange. The potential for convective heat exchange is determined by the difference between skin and air temperatures as shown by Eq. (2) and in Fig. 1A. At an air temperature of about 35 °C, where skin and air temperatures are equal, there is no convective exchange. Convective cooling increases with decrease in air temperature below 35 °C because the skin to air temperature gradient widens; at

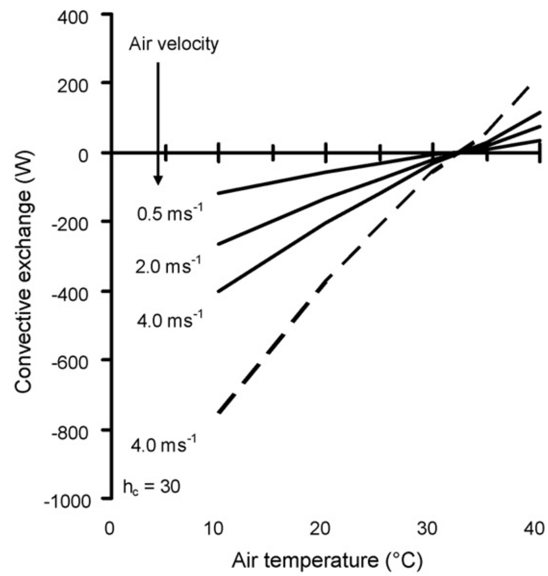

Figure 2 Convective heat exchange (C) in laboratory exercise; effects of air temperature and air velocity. Cycle ergometer; subject surface area 1.8 m^2. Air velocities 0.5, 2.0 and 4.0 m s^{-1}. Negative values denote heat loss. The broken line denotes convective exchange for free running at 4.0 m s^{-1} calculated with convective coefficient h_c = 30 (see text).[39,40] Convective heat exchange is determined by the skin to air temperature gradient (Fig. 1A), and air velocity.

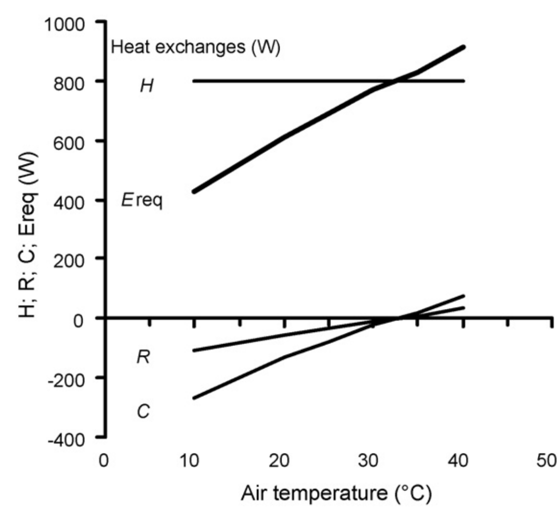

Figure 3 Evaporative requirement (E_{req}) in laboratory exercise. H is the exercise heat production; relative humidity 70%; radiant temperature = air temperature; air velocity = 2.0 m s^{-1}. R is the radiant heat transfer; C is the convective heat transfer; E_{req} is the required evaporative cooling; E_{max} is the environmental evaporative capacity. Negative values denote heat loss. Subject characteristics as for Fig. 1. Heat stress increases with increase in air temperature because of loss of convective cooling (T_a < 35 °C), or heat gain by convection (T_a > 35 °C), thus increasing requirement for cooling by sweat evaporation.

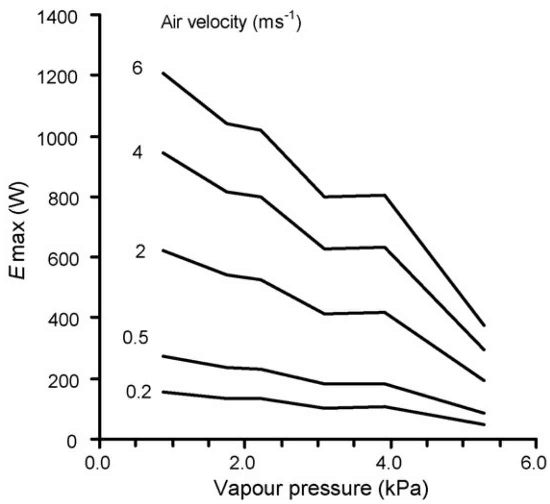

Figure 4 Evaporative capacity of the environment (E_{max}) in laboratory exercise. Subject details as for Fig. 2. Air temperatures 10—40 °C, relative humidity 70%. Evaporative capacity is determined by skin to air vapour pressure gradient (Fig. 1B), and is enhanced by air movement.

air temperatures greater than 35 °C air temperature exceeds skin temperature and convective heat exchange reverses to a heat gain. Thus in warm conditions heat stress is increased because convective cooling is restricted by the narrow gradient between skin and air temperatures, and in hot conditions, because there is heat gain from convection. Fig. 2 also shows that air movement over the skin enhances convective heat exchange. Below 35 °C increasing air velocity increases heat loss, and above 35 °C it increases heat gain. For example, at an air temperature of 25 °C, increasing air velocity with a fan from 0.5 m s^{-1} to 2.0 m s^{-1} would increase convective heat loss by about 100 W, the equivalent of reducing air temperature by about 10 °C to 15 °C at 0.5 m s^{-1}. The convective heat loss resulting from the air velocity created by free bicycling at 4.0 m s^{-1} would be about 200 W. In cool windy conditions convective heat loss may impose a risk of excessive cooling and hypothermia in lightly dressed people exercising at low intensity.

Fig. 3 shows the development of E_{req} from H, R and C with H held constant at 800 W and air velocity 2.0 m s^{-1}. It shows that E_{req} responds to any combination of H, R, and the components of C: air temperature and air velocity. Sweat rate can be estimated from E_{req} because evaporative cooling at 1 W requires an evaporation rate of 1.5 g h^{-1} (Appendix A).[4,12] In strenuous exercise H is the major component of heat stress and the thermoregulatory challenge is to unload this heat to the environment. In the example in Fig. 3, with radiant temperature equal to air temperature, small heat losses by radiation occur below 33 °C, and small gains above. At air temperature 10 °C the combined heat losses from R and C are about 400 W, so that to balance the heat production of 800 W, 400 W must be lost by the evaporation of 600 ml of sweat per hour. At air temperature about 33 °C there are no R and C losses, $E_{req} = H$ (800 W), and all of H must be lost by sweat evaporation at 1200 ml per hour. At 40 °C, R and C add about 100 W to H and E_{req} increases to 900 W. Fig. 2 shows that convective heat exchange also varies with air velocity. At air temperatures below 35 °C heat loss increases with increase in air velocity, thus reducing E_{req}, while above 35 °C, there is heat gain, and so E_{req} increases. Thus, the requirement for sweat evaporation increases with increasing environmental warmth because heat losses by R and C decrease. Consequently the environmental

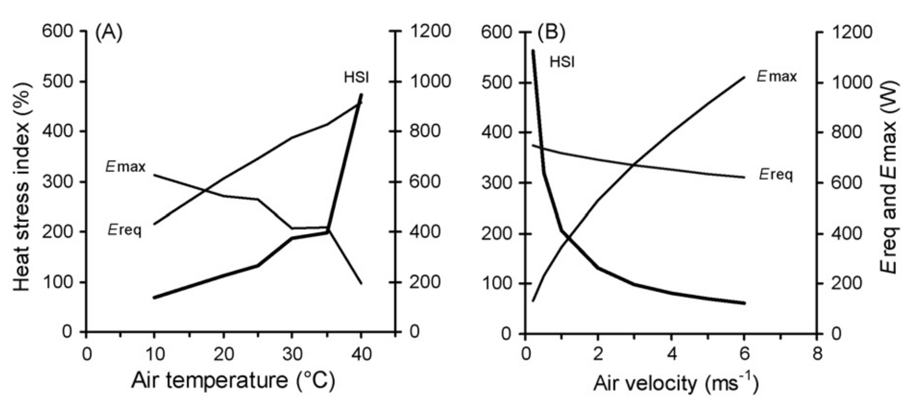

Figure 5 Integrated heat stress (E_{req}, E_{max}) and heat stress index (HSI) in laboratory exercise. H = 800 W; relative humidity = 70%; (A) Air velocity = 2.0 m s^{-1}. (B) Air temperature = 25 °C. Heat stress index = (E_{req}/E_{max})%. When E_{req} exceeds E_{max} (HSI > 100%) body temperature cannot be controlled because sweat evaporation is not sufficient to balance heat load.

evaporative capacity (E_{max}) becomes critical to thermoregulation.

Fig. 4 illustrates the components of environmental evaporative capacity. It shows that E_{max} is determined by humidity, and in particular emphasizes the critical role of air movement. As described in the Methods the vapour pressure points correspond to 70% relative humidity at air temperatures from 10 °C to 40 °C (Fig. 1B). Eq. (3) indicates that the potential for evaporation is set by the gradient in vapour pressure from the saturated pressure at the skin to the ambient vapour pressure, shown in Fig. 1B. Thus E_{max} declines with increase in humidity. Fig. 4 also shows that at all levels of humidity E_{max} is markedly restricted by low air movement. An increase in air velocity from $0.2\,m\,s^{-1}$ to $6.0\,m\,s^{-1}$ increases E_{max} at least sixfold. Thus, taking an air temperature of 20 °C and air velocity $0.5\,m\,s^{-1}$ Fig. 2 shows that C is about 50 W so that for a heat production of 800 W E_{req} is 750W. Fig. 4 shows that at the same air velocity and temperature, and vapour pressure about 1.6 kPa (RH 70%), E_{max} is only about 250 W so that thermal equilibrium cannot be achieved and heat would be stored at 500 W (750—250 W) with corresponding rise in core temperature (Appendix A). However, thermal equilibrium could be achieved by using a fan to increase air velocity to $4.0\,m\,s^{-1}$. Convective heat loss would increase to 200 W, reducing E_{req} to 600 W, but the essential benefit would arise from the increase in E_{max} to exceed 800 W. Adams[18,21] and Saunders et al.[2] have demonstrated the effect of air velocity on E_{max} in laboratory and free moving outdoor exercise.

Fig. 5 brings together E_{req} and E_{max} from the previous analysis to show the heat stress index (HSI) in relationship to environmental conditions. In Fig. 5A the apparent decline in E_{max} with increasing air temperature is because relative humidity was set at 70% so that absolute humidity increased with increase in air temperature (Fig. 1B); air temperature itself has no effect on E_{max}. At the point where E_{req} and E_{max} cross in Fig. 5A the HSI is 100% and the air temperature is about 18 °C. In this example, where $H = 800$ W and air velocity = $2.0\,m\,s^{-1}$, Fig. 3 shows that at 18 °C heat losses by R and C total about 250 W so that E_{req} is about 550 W. Fig. 4 shows that with an air velocity of $2.0\,m\,s^{-1}$ vapour pressure must be less than about 1.6 kPa for E_{max} to exceed 550 W. Since 1.6 kPa corresponds to RH 70% at 20 °C (Fig. 1B), the HSI exceeds 100% at air temperatures as low as 20 °C. In Fig. 5A HSI increases sharply at air temperatures above 35 °C (RH 70%) because E_{req} is increased by convective heat gain while E_{max} is reduced by high vapour pressure. Fig. 5B demonstrates the profound influence of air movement on heat stress. It shows that with increase in air velocity from 1 to $6\,m\,s^{-1}$ E_{req} decreases by only 150 W because at air temperature 25 °C air velocity has relatively little influence on convective heat exchange (Fig. 2). By contrast, E_{max} increases by about 650 W, from 350 W to 1000 W. For the high H in these conditions HSI at air velocity $0.5\,m\,s^{-1}$ exceeds 300%. However, increasing the air velocity to $3\,m\,s^{-1}$ brings E_{max} close to E_{req}, and a higher air velocity reduces HSI below 100%. Thus, what is intolerable in the laboratory with low air velocity would be tolerable in the air velocity created by free cycling or running. Saunders et al have demonstrated very clearly the effect of air movement on evaporative capacity for cycling in a wind tunnel. Air temperature and relative humidity were controlled at 33 °C and RH 59%, respectively. At an air velocity of $0.06\,m\,s^{-1}$ there was rapid heat storage and rise in rectal temperature, and mean cycling time, limited by rectal temperature 40 °C, was 76.7 min. With air velocity $2.75\,m\,s^{-1}$ heat storage was slower and cycling time was 108 min. When air velocity was $13.9\,m\,s^{-1}$ heat storage was minimal and cycling time extended to 120 min. With the air temperature 33 °C there was negligible convective heat loss, so that the obvious benefits of higher air velocities were almost entirely due to the increase in evaporative capacity.[2]

Figs. 2—5 demonstrate clearly that environmental heat stress is not simply a matter of high air temperature but also of humidity and, most importantly, air movement. They explain the feelings of sweatiness experienced in heat stress. During exercise in hot, dry, windy conditions sweating may be profuse because E_{req} is high, but because E_{max} is also high sweat evaporates readily, the skin is dry and there is little feeling of sweatiness. By contrast, in still, warm, humid conditions, even if exercise is light and E_{req} is low, the skin is wet and feels sticky because the low E_{max} restricts evaporation. It is largely the effect of air movement on E_{max} that explains why fans are so effective at reducing the stress and improving comfort in laboratory exercise and in tropical climates. Similarly, the air movement generated by body movement enhances E_{max} and plays a major role in reducing heat stress in sport.

Fig. 6 illustrates heat stress in free running and shows how the air movement generated by running influences heat exchanges. The increase in H with running speed is partially offset by increase in convective heat loss, which moderates E_{req}. The evaporative capacity, already at a high level at $3.0\,m\,s^{-1}$, also increases with running speed. But under the conditions of air temperature 25 °C and RH 70% E_{max} would not meet E_{req} at running speed

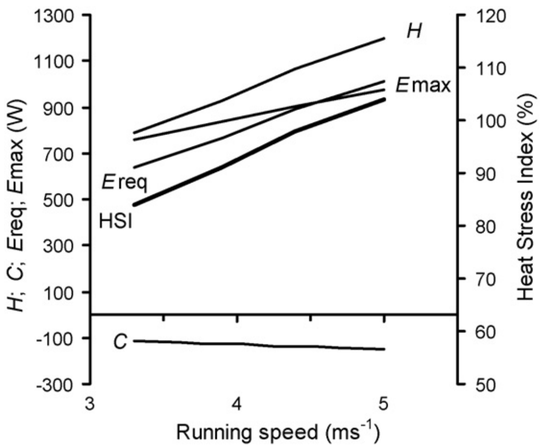

Figure 6 Heat exchanges in free running. Air temperature = 25 °C; relative humidity = 70%; vapour pressure = 2.2 kPa; air velocity = running speed. Subject characteristics as for Fig. 2, details as for Figs. 3 and 5.

>4.5 m s^{-1}. In warmer more humid conditions HSI would exceed 100% at lower speeds, while in cooler conditions thermal equilibrium could be achieved at running speeds exceeding 5 m s^{-1}. Fig. 6 also shows the potential for behavioural thermoregulation. Reduction in pace reduces the HSI. In this environment, slowing from 4.5 m s^{-1} to 4.0 m s^{-1} reduces the HSI to 90%, and although the stress remains high thermal equilibrium can be achieved. Thus, as Tucker et al.[1] have shown, heat stress may be moderated at the expense of performance.

Discussion

Rational analysis

By means of rational and systematic analysis this article provides a basis for understanding exercise heat stress. Rational analysis of heat stress is based on fundamental physical principles determining exchanges of heat between the body and the environment. It evaluates the effects of infinite combinations of all the six factors that determine heat stress. Moreover, by doing so, it reveals the principal factors determining the stress. For this reason it must be the gold standard that informs all other methods of assessing heat stress. Rational analysis has long been applied to evaluating heat stress in industry[10,33] but has not been applied to sport. Analysis of occupational heat stress requires complex algorithms to account for the industrial environment, effects of clothing and body movement.[12,34,35]. Whereas the basic forms of Eqs. (1)—(3) are appropriate to lightly dressed sports people.

Nonetheless, the reader should be aware that the values of the constants in Eqs. (1)—(3), and Figs. 2—6 generated from them, may not provide accurate predictions of heat stress in sport. Discrepancies between predicted and observed thermoregulatory strains could be due in part to inadequacies in the predictive models, and in part to variation in individual thermoregulatory responses. In practice, E_{req} can predict sweat rate moderately well. For example, in an investigation of the stresses and strains of arduous physical work in bushfire fighting in Australia, using Eqs. (1)—(3) and appropriate clothing adjustment, the regression coefficient of measured sweat rate on E_{req} with both terms expressed as g h^{-1} was 1.06 (r^2 = 0.48; p < 0.001).[36] Prediction of E_{max} is less certain. The coefficient of evaporation h_e is difficult to determine experimentally, and estimation of E_{max} is based on limited empirical observations and on the theoretical relationship between convection and evaporation.[4] Appropriate coefficients of heat exchange and the specific factors required for predicting heat stress in sports, such as metabolic rates, skin temperatures, and relative air movement have not yet been quantified.

Convective heat transfer is calculated from the convective coefficient h_c which is composed of a constant k_c and a power function of air velocity v^n ($h_c = k_c v^n$ W m^{-2} °C^{-1}), and the temperature gradient from skin to air (T_{sk}—T_a). For linear air flow over a stationary subject, conventional values for k_c range from 7.6 to 8.3, and $v^n = v^{0.6}$ (see Appendix A.1).[4,10,12,37,38] In warm conditions such variations in k_c have little effect on predicted convective exchange (Fig. 2). Convective and evaporative constants for free walking and running are greater than those in Eqs. (2) and (3) and probably vary with speed of movement. Nishi and Gagge[38] determined a convective coefficient of $8.6v^{0.53}$ W m^{-2} °C^{-1} for free walking. Clark et al.[39,40] demonstrated that in running the convective heat transfer across the swinging legs is considerably greater than would be predicted for an air flow equal to running speed over a stationary athlete. For running at 4.4 m s^{-1} (16 km h^{-1}) they determined a whole body convective coefficient h_c of 30 W m^{-2} °C^{-1}, suggesting a value of 12 for k_c. Convective heat exchange calculated for running at 4.0 m s^{-1} using this coefficient is shown in Fig. 2. De Freitas et al discuss alternative methods of estimating the whole body convective coefficient for running.[41]

The environmental evaporative capacity is closely related to convective heat exchange. The value of the evaporative coefficient (k_e) is taken as 15—16 times that of the convective coefficient (Eqs. (2) and (3)).[4,42] Thus for running at 4.4 m s^{-1},

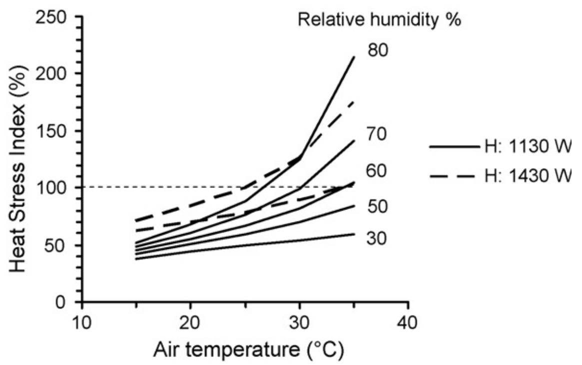

Figure 7 Heat stress index for free running at 4.5 m s^{-1} (16 km h^{-1}). Effects of air temperature, humidity and running economy. Air velocity = running speed. HSI for H: 1430 W at 50 and 70% relative humidity. HSI 100% marks upper limit of prescriptive zone for thermoregulation. Subject details as in Fig. 2.

based on a whole body k_c value of 12, the estimated evaporative constant k_e is about 185. In practice, however, the benefit of expansion of E_{max} with running may not be realized because of physiological limitation to leg sweating. Clark et al. observed that the legs may be dry even when sweat is running from the face and trunk.[40] Clearly, sweat running off the skin is not evaporating—because a physiologically appropriate sweat rate exceeds the local evaporative capacity. In effect, the body is made up of segments: the head and trunk, legs and arms. Each segment has a specific pattern of air movement resulting in local differences in E_{req} and E_{max}.[4] In some conditions, E_{max} for the fast moving legs may exceed the leg sweating capacity so that the legs are dry, while for the slower moving trunk E_{max} may be lower than the local sweat rate so that the trunk is wet with unevaporated sweat.[40]

Heat stress and prescriptive zones

Lind suggested that the upper limit of a prescriptive zone (ULPZ), where core temperature increases with further increase in environmental heat, is associated with the minimal internal thermal gradient compatible with adequate transfer of heat from the body core to the periphery.[30] Clearly a prescriptive zone is also exceeded in conditions in which E_{req} exceeds E_{max} (HSI > 100%). At high metabolic rates the cooling power of the upper limit of the PZ must be greater, and so the range of the PZ is narrower, than for lower metabolic rates.

Fig. 7 summarises heat stress, and demonstrates Prescriptive Zones, for running at 16 km h^{-1} (4.4 m s^{-1}) in sunshine (estimated R = 130 W) and a range of temperatures and humidities. Heat stress was estimated for two runners with different running economies using the convective coefficient 30 W m^{-2} °C^{-1}, and evaporative coefficient 324 W m^{-2} kPa^{-1} for a conservative estimate of E_{max} (Appendix A). Fig. 7 shows that HSI 100% and the ULPZ can result from varying combinations of air temperature and humidity, as well as air velocity, and also varies with H. For example, for the runner with H 1430 W the HSI is 100% (ULPZ) at 25 °C and RH 70%. There is convective cooling (Fig. 2) but if relative humidity exceeds 70% the vapour pressure does not provide an adequate E_{max} to meet E_{req}. The HSI also equals 100% at 35 °C and RH 50%; at this temperature there is no convective heat loss and thermoregulation depends entirely on evaporation. Nonetheless, provided relative humidity does not exceed 50% the high skin temperature and resulting humidity gradient (Fig. 1B) provide an adequate E_{max}. Although temperature control can be achieved in both these conditions the thermal stress differs substantially.[13,30,32] Skin temperature varies by at least 5 °C (Fig. 1A), with marked effect on perceptions of thermal stress,[16] sweat rate, other physiological responses and fatigue,[43]and on performance.[1] For the more economical runner, running at the same speed but with lower heat production (H 1130 W), conditions at HSI 100% are warmer and more humid.

In strongly evaporative environments (HSI < 50%) physiological sweat production is closely matched to E_{req}. In conditions in which sweat runs off the skin (HSI > 50%) sweat rate may exceed that estimated by E_{req} in an attempt to compensate for lost evaporative cooling.[2,4,12] Adjustment of predicted sweat rate for reduced sweating efficiency, may be appropriate for moderate intensity activities such as tennis,[4,12] but in high intensity exercise in warm conditions E_{req} and sweat production may already be close to maximal sweat rates.

Both the convective exchange and the evaporative capacity operating on a free moving person are usually greater than that arising from ambient air velocity alone (Figs. 4 and 5). In sports characterized by intermittent activity ambient air movement may moderate the overall heat stress during interludes of low activity. In indoor sports venues and closed-in outdoor stadia heat stress is exacerbated by the low ambient air movement.

Variation in individual thermoregulatory responses may result in differences between measured sweat rates and sweat rates predicted from E_{req}. Women and children may sweat less than men. Such people thermoregulate successfully in cool and moderate conditions by virtue of elevated skin temperatures and convective cooling.[44,45] Inevitably, in warm conditions they are disadvantaged by restricted convection. Heat acclimatization may improve the sweating response and heat tolerance, but when the environment restricts evaporation (HSI > 100%) increased sweat production is of limited benefit.[2]

Risk assessment

The present discussion assumes that the risk of developing dangerous hyperthermia is the principal concern about heat stress in sport. Prediction of core temperature is not easy in sport because it is determined by relative exercise intensity, requiring knowledge of the athlete's metabolic rate and $\dot{V}_{O_2\,max}$. No index of heat stress, of itself, can reliably predict incidence of heat casualties. Such prediction can only be achieved by determining epidemiologically the association between the incidence of heat casualties and environmental conditions.[3,46]

Presumably based on the concept of a Prescriptive Zone, many sports organizations recommend environmental indices such as the WBGT for assessing risk and setting environmental limits for training and competition.[47–49] The American College of Sports Medicine Position Stand on Heat and Cold Illnesses in Distance Running provides excellent advice on environmental considerations in the management of large road races. The recommendations also include grading of risk of heat stroke, and corresponding modifications to competition schedule and advice to participants, based on air temperature and relative humidity, or the Wet Bulb Globe Temperature (WBGT).[47] The National Athletic Trainers' Association,[48] and other sports organizations[49] recommend applying the same risk grading to sports generally. Yet there are considerable difficulties in predicting risk based only on environmental conditions. The WBGT in itself is almost entirely uninformative. It makes sense only when related to human responses such as thermal comfort, physiological strain, performance, or incidence of heat injury.[3,46,50] Without knowledge of these relationships the WBGT cannot be applied objectively to the management of heat stress in sport. Moreover the WBGT is an imperfect index of environmental stress. It does not incorporate exercise heat production, the effects of body movement or clothing.[3,51,52] Furthermore, from Fig. 7 it can be shown that WBGT values can be different for conditions in which the HSI exceeds 100%. For example, for heat production 1430 W at air temperature 25 °C and RH 70% the WBGT is about 25 °C, but at air temperature 35 °C and RH 50% the WBGT is about 34 °C. How then are hazardous levels of WBGT, that take all these factors into account, to be determined?

The heat stress at any level of WBGT varies with exercise heat production. Thus risk grading and action levels set on the WBGT, or other measures of the thermal environment, must vary with different sports, with running speed, and even with individual running economy (Fig. 7). Applied to the ACSM risk grading, slow runners with moderate metabolic rates might not be at risk in warm 'high risk' conditions, while fast runners with high metabolic rates and relative work rates might be at risk in cooler 'moderate risk' conditions (Figs. 6 and 7). Similarly, risk grading for moderate intensity sports such as tennis could be set at higher (warmer) WBGT levels than for highly energetic activities such as endurance running. Clearly, it is not appropriate to apply to all sports WBGT-based risk levels and limits that have been estimated for endurance running.

Rational analysis, providing objective sport-specific assessment of heat stress, should be the basis of environmental guidelines for sports participation. In contrast to the WBGT, rational analysis provides an objective and meaningful expression of heat stress. It predicts sweat requirements and whether core temperature can be controlled. Conditions in which HSI > 100% indicate potential action levels for modification to competition or training. Fig. 7 provides an example of the application of rational analysis to prediction of sports heat stress. Consideration of Eqs. (1)–(3) shows that with estimates of heat production, skin temperature and air velocity, figures or tables can be constructed for any sport that relate heat stress to simple measures of air temperature and humidity.

Rational analysis further highlights the inherent difficulty of assessing risk associated with environmental heat stress in sport. While an HSI > 100% indicates that control of core temperature is not possible, the absolute level of heat stress is actually revealed by the thermal imbalance, and consequent heat storage, arising from the failure of sweat evaporation to meet cooling requirement (E_{req}–E_{max}). For example, for tennis an HSI of 112% might be based on E_{req} 777 W/E_{max} 695 W resulting in heat storage of 82 W and for a 70 kg player a rise in core temperature of 1.2 °C h^{-1}. Assuming an exercise intensity of 65% $\dot{V}_{O_2\,max}$ the estimated core temperature at 30 min would be about 38.5 °C. Play could continue for another 75 min before core temperature reached 40 °C. Thus rational analysis shows that it may be safe to conduct a sports event even when HSI exceeds 100% because intolerable overheating would not occur before completion of the event, or before a break in play that allows core temperature to fall. By contrast, similar calculations for endurance running show that core temperature may rise rapidly, For example, for a

65 kg athlete running at 80% $\dot{V}_{O_2\,max}$, an HSI of 114% based on E_{req} 1314 W/E_{max} 1155 W indicates a rise in core temperature of 2.3 °C h^{-1}. Core temperature at 30 min could be about 39.5 °C, and 40 °C would be achieved in about 43 min (see Appendix A.2 for calculations).

Heat stress impacts on three aspects of sports participation: comfort, performance, and health and safety. While indices of heat stress may provide valuable guides to the severity of the stress, judged on subjective and physiological impact, their application to predicting heat casualties is less certain. In sports with moderate levels of activity the dominating impact of environmental heat stress may be discomfort and 'fatigue' associated with high skin temperature, rather than risk of hyperthermia. In high intensity exercise, feed back between physical stress and such responses may prompt reduction of exercise intensity and corresponding reduction in stress.[1,33,50,53] Thus performance impairment, rather than health risk, may be the primary effect of environmental heat stress in sport.[43] For this reason also it may not be valid to base risk assessment on exercise intensity observed in cool conditions.

Research

Evidence-based assessment of stress and risk is essential for the objective management of heat stress in sport. For this, both rational analysis of heat stress and epidemiological research are required. Sport-specific algorithms must be developed to enable objective quantification of heat stress arising from wide combinations of environmental conditions. Because of the complexities of the thermal environment acting on an athlete such algorithms can probably only be determined by empirical research.[33] Essentially, measurement of environmental conditions, energy expenditure, skin and core temperatures and sweat rates in individual sports, in a range of weather conditions, is required. In conditions in which core temperature reaches equilibrium the components of E_{req} are reflected in sweat rate, and convective heat exchange can be estimated (Eq. (2)). Conditions in which core temperature rises progressively indicate that the environmental evaporative capacity is inadequate to meet E_{req} and thus provide an indication of E_{max}. Running, walking and cycling are the simplest activities to investigate and may yield algorithms that are applicable to other sporting activities.

Epidemiological investigations of the associations between environmental conditions and perceptions of thermal comfort and fatigue, performance, and the incidence of heat casualties, are also required. Such investigations would determine the impact of factors such as behavioural thermoregulation or over-motivation and individual heat tolerance on population variations in physiological and pathological responses to heat stress.[3,33] For example, for marathon running, Ely et al.,[50] and Zhang et al.[53] have reported correlations between performance, and Roberts[46] has reported correlations between heat injury, and environmental conditions.

Conclusion

Heat stress and strain in sport are a complex mix of behaviour, physics and physiology. Heat stress arises from largely independent components that provoke specific thermoregulatory responses. (1) Exercise heat production drives body core temperature in relation to an athlete's maximal aerobic power. (2) Air temperature and thermal radiation drive skin temperature. The combined thermal stress arising from exercise and the environment are integrated to drive sweat production. (3) The evaporative capacity of the environment must allow sufficient sweat evaporation to achieve thermal equilibrium and control of core temperature. Despite these complexities, systematic analysis of physical heat exchanges can predict sweat requirements and determine whether thermal equilibrium can be achieved. The principle of rational analysis should inform the assessment of heat stress in sport. Although such analysis provides an objective basis for assessing the severity of heat stress behavioural thermoregulation and individual variation in heat tolerance make prediction of the risk to health less certain. Carefully designed empirical research is required to develop appropriate algorithms for the rational analysis of heat stress in sport.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.jsams.2007.08.017.

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