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Sweating in extreme environments: heat loss, heat adaptation, body-fluid distribution and thermal strain

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Abstract

Evaporation is an extremely powerful cooling process. When totally evaporated from the skin surface, sweat can remove body heat at a rate of 2.43 kJ«g"\ Humans therefore control sweat secretion to maintain thermal homeostasis. Since humans are capable of extended sweat rates approximating 30 g'min"1, it is possible to remove heat at rates -73 kJ-min"1. Assuming a 20% efficiency, such heat loss will support a normothermic total energy use of 1520W. This equates with an external work rate of 304W, eliciting an oxygen consumption >3.5 /«min"1. However, while man has a great capacity to both work and dissipate metabolically-derived heat, exercise under various environmental extremes may impede heat dissipation. Under such conditions, the cumulative effects of metabolic and environmental thermal loads may represent an uncompensable heat stress, predisposing to hyperthermia.

Keywords

body, adaptation, loss, heat, environments, distribution, extreme, strain, sweating, thermal, fluid

Disciplines

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INVITED LECTURE 4: SWEATING IN EXTREME ENVIRONMENTS: HEAT LOSS, HEAT ADAPTATION, BODY-FLUID DISTRIBUTION AND THERMAL STRAIN.

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INTRODUCTION

Evaporation is an extremely powerful cooling process. When totally evaporated from the skin surface, sweat can remove body heat at a rate of 2.43 $kJ\cdot g^{-1}$. Humans therefore control sweat secretion to maintain thermal homeostasis. Since humans are capable of extended sweat rates approximating 30 $g\cdot min^{-1}$, it is possible to remove heat at rates ~73 $kJ\cdot min^{-1}$. Assuming a 20% efficiency, such heat loss will support a normothermic total energy use of 1520W. This equates with an external work rate of 304W, eliciting an oxygen consumption >3.5 $l\cdot min^{-1}$. However, while man has a great capacity to both work and dissipate metabolically-derived heat, exercise under various environmental extremes may impede heat dissipation. Under such conditions, the cumulative effects of metabolic and environmental thermal loads may represent an uncompensable heat stress, predisposing to hyperthermia.

THE PHYSIOLOGICAL SIGNIFICANCE OF SWEAT

Evaporative cooling in terrestrial beings is perpetual, occurring from the respiratory tract with every breath, and via water-permeable membranes. Resting normothermic man, within a cool-temperate environment, evaporates 30-33 $g\cdot h^{-1}$ from each surface, with the corresponding cooling effect accounting for the dissipation of about 25% of the resting metabolic heat production. This occurs without our awareness: insensible evaporation. When faced with an external heat load, thermosensitive cells within the skin, and eventually those within deeper tissues, communicate this altered thermal status to the hypothalamus for interpretation. Hypothalamic integration of thermal messages results in the generation of a `load error' message, to which a proportional sympathetic response is elicited: eccrine sweating.

Apart from man, a number of species possess the ability to sweat actively in response to thermal stress. In man, considerable inter-individual differences are apparent for sweat gland densities and secretion rates [1, 2]. Indeed, men generally sweat more than women [3], and even racial differences exist [4]. While euhydrated people can sustain insensible losses indefinitely, dehydration will occur during active sweating, if water replacement is not elevated proportionately. For instance, daily sweat rates can increase from 300-400 ml, to 10-15 litres during prolonged heat and exercise exposure. Extended-duration sweating of 1.5-1.8 $l\cdot h^{-1}$ (30 $g\cdot min^{-1}$) is commonly observed and, under severe heat stress, glands can secrete up to 3-4 $l\cdot h^{-1}$.

It has been estimated that we have between 1.6-4.0 million sweat glands [5], with considerable variability in gland density between regions. Each gland consists of a secretory coil, connected to the skin surface. As sweat moves through the duct, sodium, chloride and bicarbonate ions are reabsorbed [6]. Sweating typically starts by recruiting groups of glands innervated by the same sympathetic nerve. At rest, sweating generally starts at the extremities, moving towards the head as thermal strain increases [7]. However, we have shown that, with the exception of an earlier lower torso sweat onset, between-site sweat recruitment is generally uniform during upright exercise [8]. During sustained sweating, sweat is secreted across the body surface in a cyclic pattern, reflecting the rhythm of sympathetic activity. As thermal strain rises, the frequency of glandular stimulation is elevated. During the phase conversion from liquid to gas, the water molecules do not themselves change temperature, but simply absorb thermal energy to drive evaporation. With the evaporation of 1 g of sweat, 2.43 kJ of heat is removed.

FACTORS WHICH AFFECT SWEAT EVAPORATION

The evaporation of sweat is influenced by the water vapour pressure of the surrounding air, but is mainly determined by that of the microclimate above the skin, with water passing down the vapour pressure gradient. Thus, any factor that affects this gradient will impact upon evaporative cooling. Six such factors will be covered within this presentation.

Immediately above the skin is a very thin layer of air, which behaves as though it was trapped in permanent contact with the skin: the boundary layer. For evaporation to occur, the water vapour pressure of the boundary layer must be less than that of the skin surface. Since both the size and composition of the boundary layer are an inverse function of air velocity (relative or absolute), both environmental water vapour pressure (reflected within relative humidity) and wind speed can modify evaporative cooling. The single greatest impact upon the boundary layer is brought about by the use of clothing. While some clothing ensembles allow air to pass through the fabric and apertures, less permeable garments trap air. In such ensembles, locomotion largely determines garment ventilation [9], and trapped air water vapour pressure.

The above factors represent physical changes. Evaporative cooling also depends upon physiological variations. Continuous sweating, at high flows, leads to sweat accumulation, and eventually sweat suppression (hidromeiosis: [10]). This is generally attributed to water-induced swelling of subcutaneous tissues, leading to pore blockage. Hydration status affects heat loss by reducing the core temperature threshold for sweating onset, the sensitivity of the sweat response to such changes, and local sweat rates [11]. On the other hand, adaptation to both endurance training and heat have been shown to increase sweat rates [12].

SWEATING AND BODY-FLUID COMPARTMENTS

The human body is about 60% water (500-600 $ml.kg^{-1}$: female-male), which, while stored within various compartments, is free to move between these sites. Water, the primary substrate for sweat, is drawn from this reservoir. The total volume of water stored is a function of hydration state [11], body composition [13], and endurance exercise adaptation [14]. For instance, a low adiposity is associated with the storage of a larger water volume relative to body mass, due to the higher water content of lean tissue relative to fat [13]. During exercise, we have shown that fluid losses are drawn almost equally from the intracellular and extracellular compartments [15]. The plasma volume forms a sub-division of the extracellular volume, and is generally defended in cool and temperate, but not within hot environments [15]. If not replaced, fluid losses result in progressive dehydration, impaired physiological function and dysthermia.

HEAT ADAPTATION

It was believed that heat adaptation (acclimation) might influence the regional distribution of sweating, favouring greater limb sweating. Past experiments from our laboratory have demonstrated that, while adaptation enhances sweating by elevating sweat rate and lowering its onset threshold [12, 16], it was not associated with a sweat redistribution [16]. For any site, the post-adaptation sweat responses appeared more closely related to differences in sweat gland density, than to altered control of the sweat glands.

Heat adaptation is known to affect body-fluid volumes. Typically, post-adaptation elevations in body fluid, including the plasma compartment, are observed [17]. However, until recently, it was accepted that the plasma lost during combined heat and exercise stress would be diminished following heat adaptation. We now know this to be somewhat imprecise. Instead, the post-adaptation plasma volume increase is also associated with a greater post-adaptation plasma loss [17]. We have observed that plasma losses, during heat and exercise stress, increase from 16% prior, to 22% following, extended heat adaptation [17]. Thus, the plasma volume was not preferentially defended. Instead, the heightened sweat losses and elevated resting plasma volume, resulted in an elevated plasma contribution to fluid losses following heat adaptation.

CONCLUSION

We have seen that, while the evaporation of sweat serves a very powerful cooling function, it may be impeded by changes in the boundary layer air and hydration state. On the other hand, endurance training and heat adaptation enhance sweat secretion. However, such changes need not necessarily be associated with greater evaporative cooling, which remains dependent upon the water vapour pressure gradient between the skin and the boundary layer air.

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