# Body temperature and its regulation

Andrew Sean Weller

Man is a homeotherm and, as such, deep body (core) temperature must be maintained within narrow limits throughout life, despite greater fluctuations in the ambient temperature. Although core temperature fluctuates by about 0.5°C throughout the day, only during prolonged exercise, illness and exposure to extreme hot and cold environments will it deviate outside the normal range of 36.1–37.8°C. Core temperature is normally in a state of dynamic equilibrium as a result of a balance between factors that add and subtract body heat. These factors are evident in the body heat balance equation:

Heat storage = metabolic heat production ± conductive, convective and radiant heat exchange – evaporative heat loss.

Conductive, convective and radiant heat exchange are positive if heat is gained from the environment, and negative if heat is lost to the environment. Heat storage is zero (i.e. core temperature is constant) when heat production is balanced by heat loss.

Hyperthermia is associated with a net increase in body heat content (i.e. positive heat storage), whereas hypothermia is associated with a net decrease in body heat content (i.e. negative heat storage). Homeostasis of body core temperature is accomplished through two parallel processes: behavioural temperature regulation and physiological temperature regulation. Behavioural temperature regulation operates through conscious behaviour and may employ any means available. Physiological temperature regulation operates through responses that do not rely on conscious voluntary behaviour.

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## Effector responses

The physiological effector responses facilitating homeostasis of body core temperature may be described in terms of their ability to influence heat loss and heat production.

### Heat loss

The surface of the body exchanges heat with the environment by conduction, convection, radiation and evaporation.

- Conduction involves the transfer of heat from one material to another through direct molecular contact. For example, the heat generated deep in the body core can be conducted through adjacent tissue until it reaches the body surface. It can then be conducted to clothing or air that is in direct contact with the skin. Conversely, if the matter in direct contact is hotter than the skin, heat will be conducted to the skin.
- Convection involves the transfer of heat by the motion of a gas or liquid across the heated surface. For example, air circulates around the body (even when trapped in clothing layers) and sweeps away the air molecules that have been warmed by contact with the skin. The greater the movement of air (or liquid, such as water), the greater the rate of heat removal by convection. In combination with conduction, convection can also cause the skin to gain heat in a hot environment. Although conduction and convection continuously remove heat when skin temperature is higher than air temperature, their contribution to overall heat loss is relatively low (about 10–20%). However, due to the high specific heat capacity of water, the rate of heat loss by conduction and convection is considerably greater in cold turbulent water compared with air at an equivalent temperature.
- Radiation is the primary means of dissipating heat at rest and, at normal room temperature (about 21–25°C), the nude body may lose up to 60% of its excess heat by this means. Radiant heat is emitted as infrared rays and the body continuously radiates heat to cooler objects (e.g. clothing and walls), but it may also gain radiant heat from warmer surrounding objects. The sun is a powerful radiator and direct exposure to it may cause heat gain.
- Evaporation accounts for about 20% of heat loss at rest, but may increase to about 80% during exercise. Thermal energy is required to transfer water from the liquid to the vapour state. Thus, when water vaporizes from body surfaces (e.g. lungs, mucosa and skin), the heat required to drive the process is removed from the surface, thereby cooling it. In the absence of sweating, water is lost by diffusion through the skin (insensible heat loss) and accounts for about 10% of heat loss, irrespective of the level of activity. However, as body temperature rises, sweat production increases and may reach a rate of 2–3 litres/hour for a short time. Sweating requires the active secretion of fluid by sweat glands which are under sympathetic control. However, high sweat rates do not necessarily translate into high cooling rates, if sweat evaporation is restricted. This is evident when the ambient vapour pressure is high (i.e. high relative humidity), or when clothing that is relatively impermeable to water vapour transfer is worn.

Heat loss by conduction, convection and radiation is largely determined by the temperature difference between the skin surface and the environment. To help explain heat exchange, the body is divided into two compartments: a core of deep tissues (e.g. brain, thoracic and abdominal organs) and a shell of peripheral tissues (e.g. subcutaneous fat and skin). The insulating capacity of the shell may be altered by vasomotor control and this contributes to core homeothermy. In a hot environment (and particularly during exercise), above a threshold body core temperature, active vasodilatation occurs which increases skin blood flow and reduces tissue insulation. This ensures that blood carries heat from the core to the skin, which has two effects. First, skin temperature is increased and thus the potential for dry heat loss (i.e. through conduction, convection and radiation) is maximized. Second, if sweating occurs, it delivers the heat necessary to evaporate the sweat. Although venomotor changes are not usually thought of as being thermoregulatory responses, dilatation of superficial veins increases the efficiency of heat convection from core to skin by the blood. In the limbs, deep veins receive blood from the muscles, whereas superficial veins receive blood primarily from the skin; there are also many communicating veins between the deep and superficial veins. Unlike the deep veins, the superficial veins are relatively well innervated by sympathetic fibres. Consequently, dilatation of superficial veins favours the return of blood via these vessels and increases the time available for heat exchange between the blood and skin. Both these effects promote the transfer of heat from the core to skin. However, in a cold environment, enhanced sympathetic activity causes vasoconstriction, which reduces the cutaneous blood flow and increases tissue insulation. Skin temperature, and therefore dry heat exchange, will be reduced. Although this heat-conserving mechanism helps to maintain body core temperature, the reduction in peripheral temperature (especially in the extremities) will result in discomfort and reduced performance of fine motor tasks, and may lead to peripheral cold injury (i.e. frost bite).

In a cold environment, clothing is an important component of temperature regulation in humans. The skin loses heat to the air layers trapped in the clothing; the clothes in turn pick up heat from the inner layer and transfer it to the external environment. The thermal insulating value of clothing is primarily determined by its thickness. If the thermal insulation of clothing is inadequate and when vasoconstriction is maximized, the ability to maintain thermal balance largely depends on the thickness of the subcutaneous fat layer. Individuals with a relatively thick layer of subcutaneous fat are able to maintain a large thermal gradient between the core and skin surface. This is particularly important during immersion in cold water, which has high thermal conductivity.

#### Heat production

Although heat conservation by enhanced vasoconstriction is an important physiological adjustment to cold stress, unless the cold stress is mild, the body must additionally increase its rate of heat production through shivering to maintain thermal balance. Shivering thermogenesis is controlled by motor innervation, and many aspects of this process are unusual and complicated. It is an involuntary response of skeletal muscles which are normally under voluntary control. Shivering can be influenced by conscious control, and it can start or stop abruptly irrespective of changes in skin temperature. Heat production is optimized during shivering as it has low mechanical efficiency and most of the heat generated appears as heat. However, compared with vasomotor responses, it is an energy-demanding process, the increase in blood flow to the shivering musculature will reduce tissue insulation, the associated limb movement will increase convective heat loss, and the performance of fine motor tasks will be impaired. Shivering thermogenesis can potentially increase the rate of heat production up to five times the resting level during cold exposure, although typically, three- to four-fold increases are observed.

Non-shivering thermogenesis is the increase in heat production independent of muscle activity. The site and mechanism of non-shivering thermogenesis in man is controversial. However, it is likely to be confined to the release of the hormones adrenaline, noradrenaline and thyroxine, which all increase the metabolic rate. Nevertheless, the contribution of non-shivering thermogenesis to heat production in the cold is minimal compared with shivering thermogenesis.

### Body temperature heterogeneity

Fundamental to the study of temperature regulation is the assessment of body core temperature (the regulated variable). However, there is no one representative body core temperature, because the temperatures of sites within the body core are slightly different from each other. Nevertheless, temperatures at all sites are within about 1°C of central blood temperature at thermal steady state. Brain temperature cannot be measured directly in man, and body core temperature is usually measured at the oesophagus, rectum, mouth, tympanum and auditory meatus.

Oesophageal temperature, which is assessed by a sensor passed through the nose and throat to the level of the left atrium, is recognized as the best non-invasive index of body core temperature, because it responds rapidly to changes in central blood temperature. However, it cannot be tolerated for long periods, and it is influenced by anything ingested while measurements are being made.

Rectal temperature, which is measured by placing a flexible sensor 5–20 cm beyond the anal sphincter, is about 0.2–0.5°C higher than the temperature of the blood leaving the left side of the heart, and responds more slowly to thermal transients (it has a time lag of 5–10 min). However, it is well tolerated for long periods and is recognized as a reliable measure of body core temperature in conditions of thermal steady state.

Sublingual temperature is widely used in the clinical setting because the tongue's high blood flow makes it an efficient heat exchanger with central blood and it is convenient to measure. However, oral temperature may be biased by head and facial skin temperature.

Tympanic temperature is assessed by a sensor placed on the tympanic membrane, which is uncomfortable and may occasionally result in damage to the membrane. Consequently, most researchers have chosen to measure the temperature of the external auditory meatus. Owing to the large temperature gradient along the wall of the meatus, the sensor must be placed near the tympanic membrane and insulated from the environment with a plug of cotton wool. The temperature of the tympanic or auditory meatus responds faster to changed core temperature than rectal temperature and, because this region receives the same blood supply (internal carotid artery) as the hypothalamus, it has been suggested that it is a valid measure of the blood influencing the central thermoreceptors.

Although skin temperature is not the regulated variable, it contributes to the effector responses directly and indirectly. Skin temperature influences the effector response even if the temperature at the site where the effector response is measured is unchanged. Therefore, the skin temperature over the rest of the body contrib-

 