Body temperature and its regulation

James Kuht

Andrew D Farmery

Abstract

Humans are homeotherms, i.e. they fix their temperature regardless of their environment. This is vital for normal cellular function and for metabolism to be independent of external temperature. The body has a warm 'core' and a cooler peripheral 'shell' whose role is to regulate heat transfer in and out of the core. Body temperature is controlled by a feedback system with both peripheral and central sensors, and an integrator located in the hypothalamus. Anaesthesia exposes patients to thermoregulatory challenges due to enhanced heat loss from the core to the shell to the environment, and interference with the hypothalamic temperature 'set-point'. In extreme circumstances, deliberate hypothermia may provide benefits that outweigh the risks.

Keywords heat loss; temperature regulation; thermoregulation; hypothermia

Royal College of Anaesthetists CPD matrix: 1A01

Learning objectives

After reading this article, you should be able to:
- understand why the human body maintains a core temperature within defined limits (*homeothermy*)
- understand the mechanisms responsible for maintaining homeothermy
- explore the consequences of deviations from optimal core body temperature and when these may occur
- understand the effect of anaesthesia and surgery on body temperature regulation

Why is body temperature important to maintain?

Man is a *homeotherm*: an organism that maintains a fairly constant core body temperature, largely independent of its environment. In our case, this core temperature is usually between 36.1 °C and 37.8 °C, and it varies with a well-defined circadian rhythm, being 0.5 °C cooler in the early hours of the morning than it is in the late afternoon. In women there is also an element of monthly rhythm to body temperature, with core temperature rising around 1 °C following ovulation.

The reason for homeothermy is the temperature dependence of the enzymatic reactions underlying all cellular functions. At higher temperatures (>42 °C) cellular proteins are damaged and cells die, whereas when cooler (<36.1 °C), the rate of reactions drops – reducing cell, and hence bodily, function (see Figure 1).

The shell and the core

To understand the regulation of body temperature, one must think of the body as two separate compartments:
- a *core compartment* containing the main heat producing organs at rest; the brain, thoracic and abdominal compartments
- a *peripheral shell* comprising the skin and subcutaneous fat, most importantly that of the limbs, that is cooler and acts as insulation for the core compartment.

The core compartment contains those organs most susceptible to temperature damage, and the relative importance of protecting this internal milieu is illustrated somewhat by the finding that responses to 1 °C change in core temperature are nine times that of responses to 1 °C changes in peripheral temperature.

Heat is transferred between the two compartments via the circulation, and in this article the specialized mechanisms of the two compartments to preserve and generate, or dissipate heat energy, shall be explored.

How is a change in temperature sensed?

Body temperature regulation functions as a feedback loop system. The set point is defined by the hypothalamus, and it is here where integration of error signals from the central and peripheral temperature receptors is thought to occur, and most effector responses originate (see Figure 3).

Situated in the walls of the third ventricle, superior to the pituitary gland, the hypothalamus contains the most important central temperature receptors, but there are also contributions from temperature receptors in the spinal cord, abdominal viscera and in the walls of the great vessels. These centrally positioned temperature receptors predominantly respond to temperature rises, as might be expected given that an upward deviation in core temperature is potentially more injurious than a downward one.

The peripheral temperature receptors are situated in the skin. With a rapidly adapting firing pattern, there are both cool receptors (maximally firing at 25 °C) and warm receptors (maximally firing at 44 °C); however, the cool receptors predominate. Their signals are transmitted via the spinothalamic tract in the spinal cord to the thalamus, and then to the hypothalamus.

The integration of these two inputs occurs in the hypothalamus, and whereas the anterior hypothalamus (preoptic area) is thought to trigger mechanisms of heat loss, the posterior hypothalamus promotes heat conservation and generation.

How is body temperature altered?

To explain how these mechanisms of heat loss or conservation occur, it is necessary to understand the various modes by which heat transfer can occur. These phenomena are listed below, with

James Kuht BA (Oxon) is a Senior Scholar in Physiology, Wadham College, Oxford, UK. Conflicts of interest: none declared.

Andrew D Farmery BSc MA MD FRCA is a Fellow and Tutor in Medicine and Physiology, Wadham College, Oxford, UK. Conflicts of interest: none declared.

the percentage heat loss each contributes to a naked human in an ambient temperature of 21–25 °C given in parentheses.

- *Radiation* (60%) – this involves the transfer of energy by infrared rays from a hotter body to a cooler one. Although a major component of heat loss for naked man at 21–25 °C, man can also absorb radiant heat in direct sunlight or from open fire or radiator. As

$$\text{Radiant heat loss} \propto (\text{Temperature difference between two bodies})^4$$

it is clear that reducing the temperature of the peripheral shell, such that it is closer to the ambient temperature, can drastically reduce radiant heat loss.

- *Evaporation* (20%) – water requires heat energy to convert it from a liquid to a vapour. This is called the *latent heat of vaporization* and for water has a value of 538 kcal/kg. Daily insensible loss is around 800 ml at rest, but as shall be explored later, sweating can drastically increase this form of heat loss.
- *Convection* (15%) – this involves transfer of heat by the motion of a gas or liquid across a surface, sweeping away skin-warmed air molecules. Normally this can be minimized by clothing, which traps the air next to the skin. A strong wind can increase convective heat loss markedly – hence the term 'wind chill' and its use in weather forecasts for indicating what the temperature will actually feel like.

$$\text{Convective heat loss} \propto \sqrt{\text{wind velocity}}$$

- *Conduction* (5%) – describes the heat transfer between molecules directly in contact with one another. Very little heat is lost or gained by this route usually, as air is a poor conductor. However, water is a 25 times better conductor, and hence water immersion at 10 °C can lead to death in just 2 hours.

When combining these modes of heat transfer, it is clear that;

$$\text{Body heat} = \text{metabolic heat production} \pm (\text{conductive, convective and radiant heat exchange}) - \text{evaporative heat loss}$$

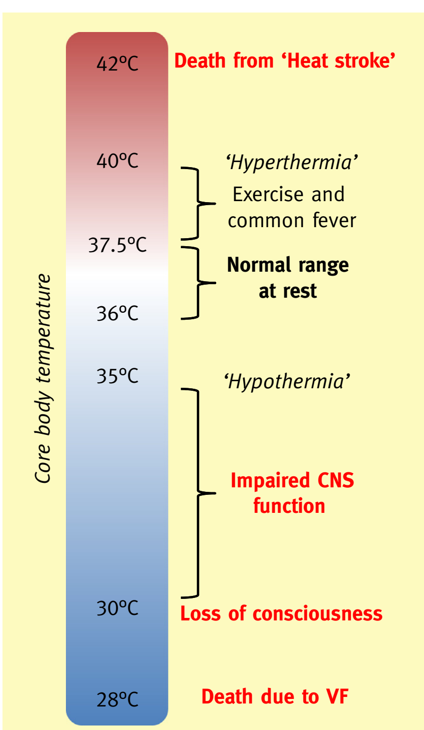

Figure 1 Illustration of the normal variation in core body temperature, and the consequences of quantitative deviations from this norm.

Heat loss by conduction, convection and radiation are largely determined by temperature difference between the skin surface and environment. Hence by affecting the temperature of the outer shell, by altering the *amount* of warm blood flowing through it and *how close this blood gets to the surface*, the rate of heat loss can be controlled.

Heat conservation for naked man

A cold stimulus causes a peripheral vasoconstriction to reduce the temperature of the skin and therefore the conductive, convective and radiant heat loss from it. This is triggered by the hypothalamic stimulation of the sympathetic nervous system.

As well as decreasing the total amount of warm blood flowing through the skin vessels, the remaining blood is redirected. Arteriovenous (AV) anastomoses that exist to allow blood to flow from arteries into more superficial skin veins are constricted, as are the superficial veins themselves to prevent communication of blood from the deep veins, thus keeping the majority of blood in the limbs within these deep veins. Deep veins run alongside the arteries and hence heat exchange occurs in a countercurrent mechanism, conserving core body heat – but leaving you with cold extremities!

When a specific threshold of cold stimulus is reached the hypothalamus employs other heat generating mechanisms to augment the heat conserving effect of vasoconstriction, these are listed below.

Heat generation

- *Basal heat production*: the energy cost at rest of breathing, heartbeat etc. amounts to between 1000 and 2000 kcal/24 hours dependent on sex (less in women, as they have proportionally more fat than men), declines with age (decrease in lean mass), and is proportional to body size.
- *Muscle activity*: is the main mechanism for extra heat production in the cold. This can be involuntary in the form of shivering, which can increase heat production to four times the normal level, or voluntary where exercise can increase heat production up to 20 times that of resting

