Body temperature and its regulation

Iain Campbell

Abstract

Body temperature is regulated to a ‘set point’ that is determined by the hypothalamus. The precise value of this set point has a circadian rhythm and is also affected (increased) by trauma and sepsis. In thermoregulatory terms, the body is thought of as a ‘central’ compartment containing all the heat-producing viscera, contained in a cooler ‘shell’ that consists of skin and subcutaneous tissue, particularly the arms and legs. Heat is generated by basal metabolism, by muscle contraction (shivering, voluntary activity and behaviour), by intake of food and, in the neonate, by non-shivering thermogenesis (brown adipose tissue). The input to the hypothalamus comes from receptors which respond to heat and cold. The receptors responding to heat are predominantly in the central compartment, that is, spinal cord, hypothalamus, abdominal viscera and great vessels; the cold receptors are largely in the skin. Heat is conserved by vasoconstriction of the peripheral blood vessels, thus creating the shell, and is lost by conduction, convection, radiation and sweating. Core temperature can be measured at a variety of sites – tympanic, external auditory meatal, nasopharyngeal, oesophageal, rectal, axillary and sublingual. All have their advantages and disadvantages and all have slightly different values.

Keywords behaviour; core temperature; hypothalamus; peripheral temperature; sensors; shivering; vasoconstriction

Man is a homeotherm and normally functions with a ‘core’ (hypothalamic) temperature between 36.1°C and 37.8°C. Body temperature varies slightly between different individuals, and fluctuates during the 24-hour day by about 0.5°C; there is a well-defined circadian rhythm with a minimum in the early hours of the morning and a maximum in the late afternoon. There is also a monthly rhythm in menstruating women; body temperature rises by 1°C following ovulation.

Regulation of core temperature around 37°C ensures optimal physiological function as cellular enzyme reaction rates are temperature dependent. The ability to defend one’s body temperature ensures that homeostasis is maintained over a wide range of environmental conditions. Naked man can maintain a core temperature of 37°C over a range of (dry) environmental temperatures between 12°C and 60°C.

__Iain Campbell__, MD, FRCA, is Consultant Anaesthetist at the University Hospitals of South Manchester NHS Trust and visiting Professor of Human Physiology at Liverpool John Moores University. He qualified from Guy’s Hospital Medical School, London, and trained in anaesthesia in Zimbabwe, Southend, Montreal and Leeds.

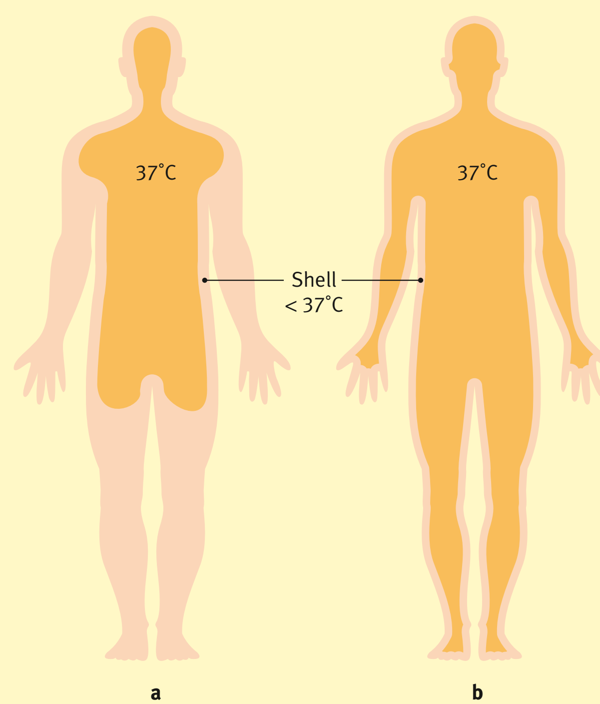
Cellular function slows down with hypothermia: human energy expenditure falls by 13% for every decrease of 1°C in core temperature. Physiological function diminishes much below 36°C and consciousness is lost below 32°C. Death can ensue anywhere below 28°C, usually due to ventricular fibrillation. Fever or severe exercise can be associated with temperatures of 40°C or even 41°C, but a core temperature much higher than 42°C is associated with breakdown of cellular proteins and death.

Man’s adaptation to extremes of environmental temperatures are largely behavioural – he builds a fire, puts on more clothes and stays indoors, or alternatively he removes clothes, turns on a fan or the air-conditioning and may immerse himself in water. Maintenance of body temperature in less extreme conditions is a result of the balance between heat gain, heat loss and the physiological mechanisms controlling these processes.

Heat conservation and dissipation: central and peripheral compartments

Thermally, the human body is considered to be a two-compartment model: a central or core compartment and a cooler peripheral one (Figure 1). The core consists of the brain and the abdominal and thoracic cavities, which contain the large organs that under resting conditions are the main producers of heat. The

Peripheral vasoconstriction



In the cold **a**, and in response to stimulation of cold receptors, peripheral vasoconstriction, which is under the control of the sympathetic nervous system, produces a cooler peripheral area or ‘shell’ of skin and subcutaneous fat, in the arms and legs particularly, that surrounds and insulates the warmer central compartment. In the warmth **b**, blood vessels to the skin dilate and skin temperature may approach central temperature

Figure 1

peripheral tissues – the skin and subcutaneous fat, particularly of the arms and legs – are cooler and act as insulation for the core compartment. Under normal thermally comfortable conditions, the temperature of the peripheral tissues is about 5–6°C lower than the central compartment.

Heat is transferred from the central to the peripheral compartments, or conserved in the central compartment, via the circulation. A cold stimulus leads to peripheral vasoconstriction, mediated by the sympathetic nervous system, and heat conservation, and a warm stimulus leads to peripheral vasodilatation and heat loss. In extreme environmental temperatures, skin temperature may approach central temperature in the heat, or 0°C in the cold. Blood flow and heat loss through the periphery is enhanced by the presence of arterio-venous anastomoses which increase flow, and thus enhance heat loss, via superficial veins in the skin. In the cold, deep veins which run alongside the arteries supplying the limbs take heat from the warm arterial blood supplying the extremities, thus leaving the extremities cold but conserving body heat – an example of a 'countercurrent' mechanism.

Heat production (Table 1)

There are a limited number of ways that man can produce heat, or increase his heat production. Basal heat production (heat production associated with the maintenance of life – energy cost of breathing, heartbeat, maintenance of cell membrane potentials, etc.) amounts to between 1000 and 2000 kcal/24 hours dependent on sex (less in women, who have proportionately more fat that men), declines with age (from about 6 months) and is dependent on body size.

Muscle contraction is the principal mechanism for increasing heat output in the form of shivering and/or voluntary exercise. Shivering is an involuntary response of skeletal muscles, which are normally under voluntary control. It can increase heat production to five or six times the resting level, although typically increases of three- to fourfold are normally seen. It is an effective way of increasing heat production as it has low mechanical efficiency, but it is energy consuming and is associated with an increase in blood flow to the shivering muscle and increased convective heat loss. Voluntary muscle contraction, such as exercise, increases heat production. With severe exercise this can be up to 20 times resting levels.

Dietary-induced thermogenesis is the energy cost of digesting and assimilating food. With a normal mixed diet, resting energy expenditure (heat production) rises by 10–15% after a meal, and is greatest after protein ingestion.

Non-shivering thermogenesis is heat production by brown adipose tissue (BAT), which is situated above the kidneys and surrounding the great vessels above the heart. BAT is brown because it is rich in mitochondria. These mitochondria are 'uncoupled', which means that instead of producing adenosine triphosphate (ATP) they produce heat under the control of the sympathetic nervous system. Non-shivering thermogenesis is a means of thermoregulation (heat production) in the hibernating rodent and neonatal man and up to the age of 6 months, but not beyond that.

Hormones are also used to increase heat production. Thyroxine has long-term control of the metabolic rate, but heat production is increased acutely by the two hormones epinephrine and norepinephrine. The mechanism is probably mediated by a number of metabolic pathways such as glycogenolysis, lipolysis (associated with triglyceride–free fatty acid cycling), gluconeogenesis and stimulation of membrane Na^+/K^+ ATPase.

Mechanisms of heat production

Mechanism	Effect
Basal metabolism	Minimum heat production (metabolism) for maintenance of life. Magnitude depends on body size, age and sex
Muscle contraction	Shivering and voluntary (behavioural) activity
Dietary-induced thermogenesis	Heat production rises by 10–15% following nutrient (food) intake. Particularly marked with protein
Non-shivering thermogenesis	Hibernating animals and neonates. Sympathetic stimulation of 'uncoupled' mitochondria in brown adipose tissue
Hormonal	Thyroid controls overall basal metabolism. Catecholamines increase heat production by stimulation of various metabolic pathways

Table 1

Heat loss

Heat exchange with the environment occurs via the physical processes of radiation, conduction, convection and evaporation.

Radiation is the transfer of energy by infrared rays from a hotter body to a cooler one. In man, it is the principal means of dissipating heat at rest. For a naked body at room temperature (21–25°C), about 60% of excess heat is lost by this means. Heat can also be gained from the environment by radiation from the sun or any artificial means of heating, such as an open fire or a 'radiator'. The amount of heat lost from a hotter body to a cooler one is a function of the fourth power of the temperature difference.

Conduction is the transfer of heat between molecules that are in direct contact. Heat generated in the larger organs such as the liver is conducted through the tissues to the surface. Lying on a cold operating table made of a conductive material or immersion in cold water would both lead to significant heat loss by conduction. Likewise, heat from a warming blanket maintained at 42°C results in heat gain by conduction.

Convection involves the transfer of heat by the motion of a gas or liquid across the surface of the skin. This sweeps away air molecules warmed by contact with the skin. Normally minimized by clothing, which traps the air next to the skin, the contribution of convection to heat loss is usually relatively small at 10–20%. In activities such as cycling or running when air moves over the

