Chapter 2 – Thermoregulation

by

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Humans belong to a group of animals called "*homeotherms*". To ensure optimal physiological function and survival, these animals must regulate their deep body temperature within a narrow range despite large changes in environmental temperatures. To do this their heat loss and heat production must be balanced; if it does not they

will become hyperthermic (hot) or hypothermic (cold), with consequences that range from mild impairment of performance to death.

The equation which describes heat balance is:

M-(W) = R ±C ±K– E

where:

M = metabolic rate.
W = measurable external work.
R = heat exchange to and from (±) the environment by radiation (R).
C = heat exchange to and from (±) the environment by convection.
K = heat exchange to and from (±) the environment by conduction.
E = heat loss (-) to the environment by evaporation.

The unit for each term is generally quoted as watts per square metre of body surface area (W.m-2).

- **M(*Metabolism*).** The chemical reactions of the body liberate energy during metabolism. The biggest cause of variation in energy expenditure is exercise. About 75% of the chemical energy used during muscular contraction is converted to heat.

- **R(*Radiation*).** All objects possessing heat emit thermal radiation from their surfaces in the form of a wave of energy containing particles within the red-infrared range of the electromagnetic spectrum. The energy from these particles are absorbed by, and transferred to, the atoms of objects they come into contact with. No medium is required for the transfer, thus, radiation is the process by which the energy of the sun travels through the vacuum of space to reach earth.

- **C(*Convection*).** In a naked person standing in cool air (below skin temperature), air molecules coming in contact with the body will be warmed, the density of the warmed air is reduced causing it to rise and be replaced with cooler air. This process is called "*natural (or free) convection*". Convective heat exchange is increased by: air (wind) or water (current) movement across the skin (this is called "*forced convection");* or the movement of the body in air or water ("relative wind speed/water current"). The exchange of heat between a body and its environment through convection depends on the temperature gradient between the two and the relative movement of the fluid (air or water) in which the body is placed.

- **K(*Conduction*).** This term is used to describe heat exchange between the skin and surrounding surfaces with which it touches. Usually the amount of heat exchanged in this way is small and is dependent upon:

  a) The temperature gradient between the skin and the surface with which it is in contact;

  b) The surface area in contact; and

  c) The thermal conductivity (ease with which heat moves through a substance) of the surface in contact with the skin.

- **E(*Evaporation*).** Evaporation is the process by which energy transforms liquid into a gas. Thus, evaporative heat exchange only occurs when fluid evaporates from the surface of an object. The heat

required to drive this process is removed from that surface and it is cooled. This is termed the "*latent heat of vaporization*", for water it amounts to 576 kcal.L-1 (2,408 kJ.L-1). The rate of evaporation depends on:

a) The skin surface area that is wet;

b) The air movement around the body (wind or body movement); and

c) The difference between the vapour pressure at the skin surface and that in the air.

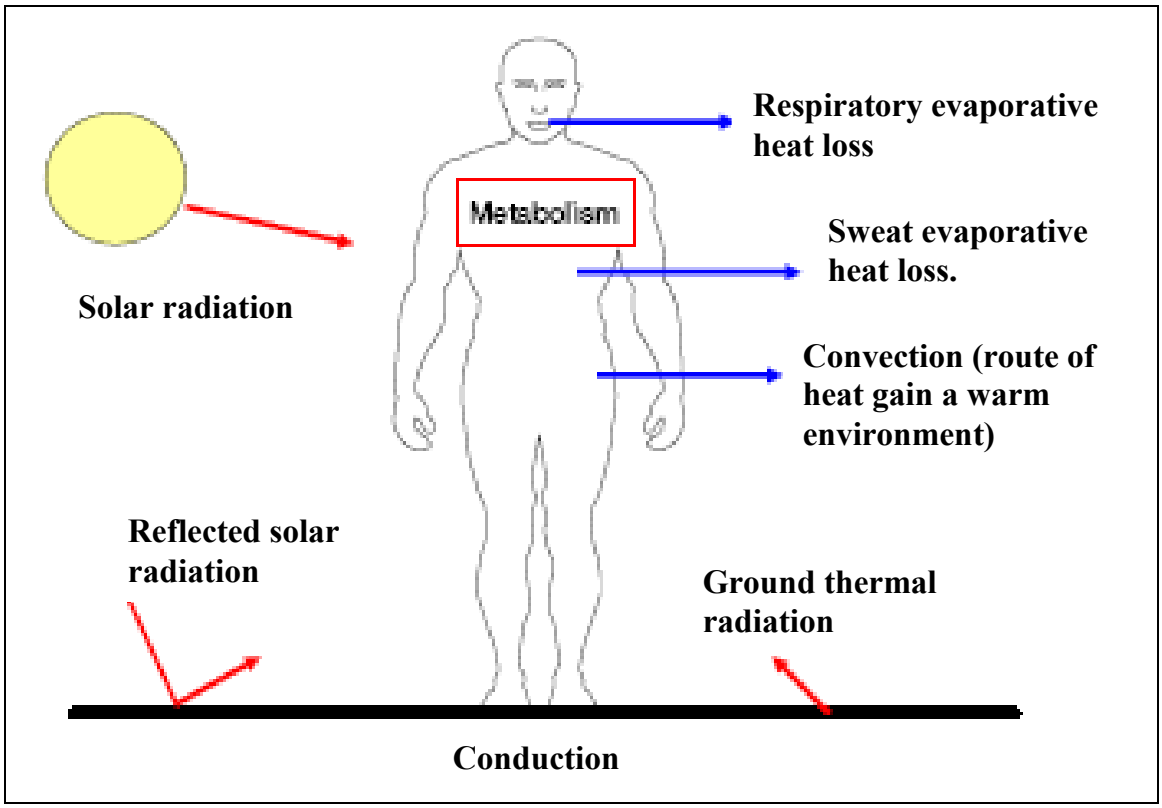

Figure 2-1: Heat Exchange in a Thermoneutral Outdoor Environment (e.g. 25°C, rh 50%) Red = Heat Gain; Blue = Heat Loss from the Body.

PHYSIOLOGICAL REGULATION ("*THERMOREGULATION*")

In humans, it is the role of the *thermoregulatory system* to vary the level of heat exchange with the environment so as to maintain deep body temperature within about half a degree Celsius of the normal deep body temperature of 37°C (98.6°F). The body defends its temperature with some vigour and the thermoregulatory system can take precedence over other regulatory systems. For example, body temperature is maintained during starvation, when energy could be saved by permitting body temperature to fall; blood pressure regulation can fail due to increased circulation to the skin ("*vasodilatation*") in the heat; and sweating is maintained when the body is depleted of water ("*dehydration*"), when cessation of sweating would conserve water.

In order to control body temperature the thermoregulatory system must be able to sense temperature and respond to changes. Thus, it includes receptors that respond to rises ("*warm receptors*") and falls ("*cold receptors*") in temperature. These receptors can be found in areas of the body such as the skin, muscles, spinal cord, and brain. In the skin for example, there are about three times more cold than warm receptors. They are located about 0.18 mm below the surface of the skin; this means that they respond quickly to changes in environmental temperature. In contrast, in the area of the brain that is particularly sensitive to temperature, called the "*hypothalamus*", there are more warm than cold receptors. These are not stimulated until changes in environmental temperature, or metabolic heat production (e.g. exercise), have an impact on the temperature of the brain via the blood flowing through it.

The thermoregulatory responses evoked are the result of an integration of the inputs from peripheral and central receptors, this integration occurs in the hypothalamus. Thus, the hypothalamus is not only sensitive to its own temperature, it also receives and processes thermal information from the remainder of the body and initiates appropriate responses. The temperature receptors in the brain are more important in determining the type and magnitude of thermoregulatory responses than those in the periphery. This relationship has practical consequences and, for example, explains why hand cooling can be used to cool a hyperthermic individual, but not to re-warm a hypothermic one.

THE RESPONSE OF THE BODY TO FALLING TEMPERATURE

Because we are primarily interested in survival in the sea, the response to cooling are described below.

Increased Heat Conservation

Alteration in Peripheral Blood Flow

When cold, the body shuts ("*vasoconstricts*") the blood vessels in the skin. This reduces blood flow to the skin and the underlying fatty layer. In so doing, it converts both into an insulating buffer zone on the surface of the body that protects the inner "core" temperature where the vital organs are situated. Insulation is defined as resistance to heat flow, and the thicker the layer of fat beneath the skin ("*subcutaneous fat*") the better the resulting insulation in the cold. Thus, reducing skin blood flow is the means by which peripheral insulation is employed. The fat beneath the skin can be regarded as "fixed" insulation that changes little in the medium term. It provides approximately the same insulation as cork (1.5 Clo/cm fat). Muscle can also provide significant levels of insulation when it is relatively unperfused by blood, i.e. at rest. However, this source of insulation is lost at relatively low levels of exercise; this includes shivering. The reduction in skin blood flow decreases the amount of heat delivered to the surface of the body. As a consequence skin temperature is lowered and becomes closer to the temperature of the environment; this reduces the gradient down which heat can be lost to that environment.

Increased Heat Production

Shivering

Shivering is the involuntary, synchronous and rhythmic contraction of small parts of skeletal muscles called "*motor units*". These contract at a rate of about 10 – 20 per second and out of phase with other units. The contractions alternate with motor units of opposing muscles and, as a consequence, large movements are avoided and no external work is done. Heavy shivering may be interspersed with periods of light shivering or rest in the early phase of cooling, but later becomes continuous before progressing into an almost tonic state.

At its maximum, heat production from shivering can reach five or six times resting levels. However, this level of shivering heat production cannot be maintained for very long.

As no external work is performed, all the energy liberated by shivering appears as heat. Some of this heat is immediately lost to the environment, however in most situations shivering can be an effective, if uncomfortable, way to maintain body temperature.

The energy needed for shivering comes from fats and sugar. Of the two, it is sugar (carbohydrate) that is in the shortest supply and, when it runs out, shivering stops. Even with moderate levels of shivering this can occur in as little as 7 hours when no food is eaten. Shivering is also reduced when oxygen levels in the inspired air fall, or carbon dioxide levels increase; this becomes important in situations where ventilation can be inadequate, such as in life rafts. Shivering uses the same skeletal muscles as voluntary exercise and the two can co-exist up to moderate levels of voluntary activity. With mild cooling, shivering is progressively inhibited as exercise intensity increases. With severe cooling the increase in muscle tone associated with shivering can inhibit co-ordinated movement and impair activities such as swimming.

In cold climates, should the heat being produced by the body be unable to balance that being lost to the environment, body temperature will inexorably decline and death from hypothermia will occur when deep body temperature has fallen by about 12°C (22°F).

FACTORS INFLUENCING THERMOREGULATION

It is evident from the above that the thermoregulatory system is influenced by thermal factors such as skin and deep body temperature. However, a wide range of "non-thermal" factors also affects it (Table 2-1). Some of these alter the way the thermoreceptors in the hypothalamus respond to changes in temperature. Others, such as fitness, alter the body's ability to produce heat or sweat. Each can alter the onset of sweating and shivering, and the sensitivity of these responses.

Table 2-1: Non-Thermal Factors that Influence the Thermoregulatory System

Age	Gender	Fitness Levels
Illness	Injury	Intoxication (Drugs/Alcohol)
Hypoglycaemia (low blood sugar)		Adaptation to Heat/Cold
Raised ambient carbon dioxide / Lowered ambient oxygen		

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