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Homeostasis (Thermoregulation)

By

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Homeostasis literally means "same state" and it refers to the process of keeping the internal body environment in a steady state, when the external environment is changed. The importance of this cannot be over-stressed, as it allows enzymes etc to be 'fine-tuned' to a particular set of conditions, and so to operate more efficiently. Much of the hormone system and autonomic nervous systems is dedicated to homeostasis, and **their action is coordinated by the hypothalamus**. Here we shall look one example of homeostasis out of **three** examples of homeostasis, in detail:

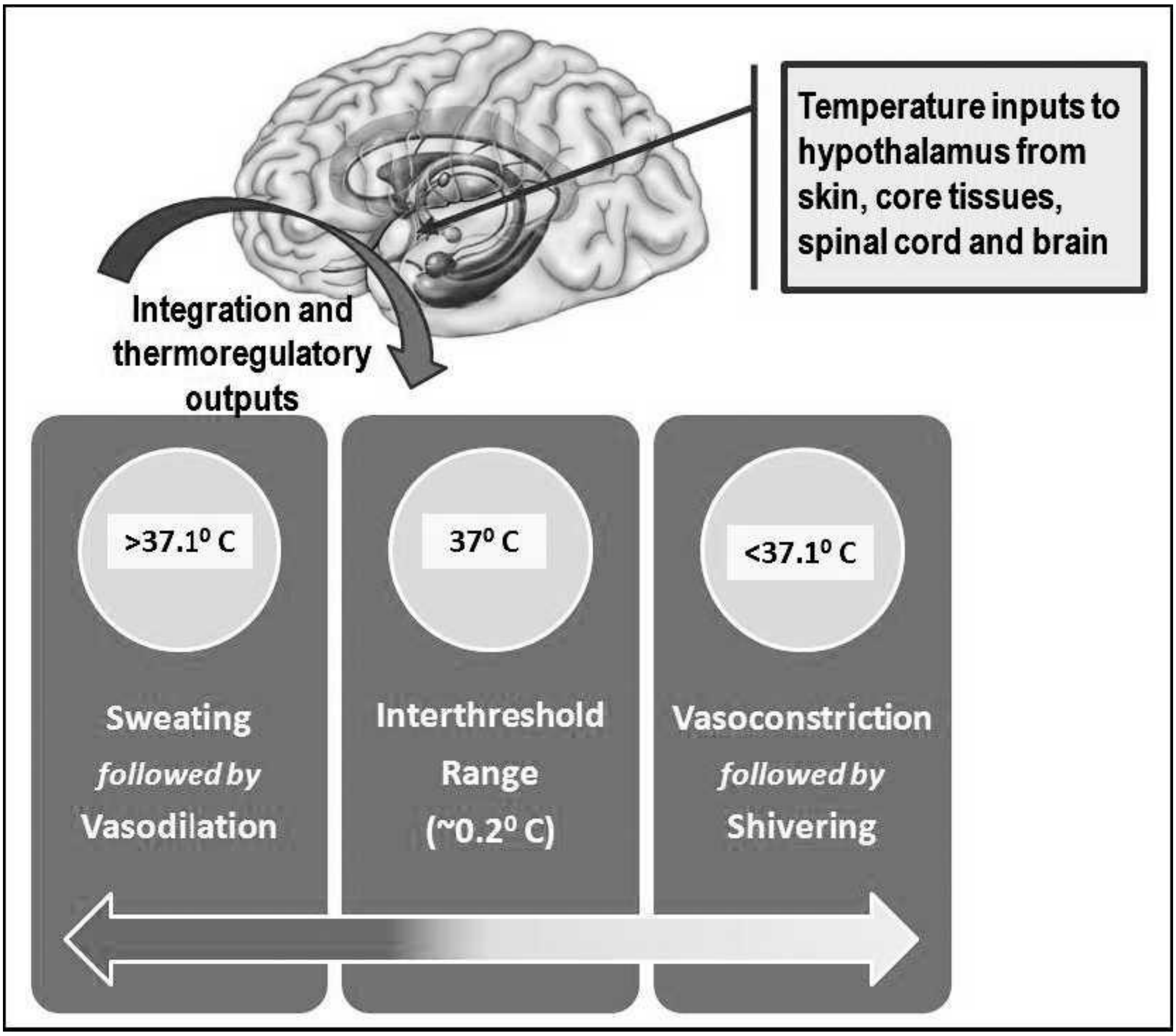
- **Temperature,**
- **Blood glucose** and
- **Blood water**.

PHYSICS OF HEAT TRANSFER

Heat loss occurs primarily from the skin of a animals/persons to the environment through several processes, including radiation, conduction and convection, and evaporation.

Of these, radiation is most significant and accounts for, 60% of total heat loss. Radiation is emitted in the form of infrared rays, a type of electromagnetic wave. Heat from core body tissues is transported in blood to subcutaneous vessels, where heat is lost to the environment through radiation. This manner of heat loss is the basis for the familiar technology used to sense and identify the locations of persons in buildings who are out of normal view. Radiation is the major source of heat loss in most surgical persons.

Conduction refers to loss of kinetic energy from molecular motion in skin tissues to surrounding air. Water absorbs far more conducted heat than air, and this accounts for more rapid hypothermia during accidental drowning, as well as the efficacy of water baths to cool hyperthermic persons. For this to be effective, warmed air or water must be moved away from the skin surface by currents, a process called convection. This accounts for the cooling effect of wind and laminar air flow in many surgical suites. Conduction and convection account for, 15% of body heat loss.



Roughly 22% of heat loss occurs by evaporation, as energy in the form of heat is consumed during the vaporization of water. Water evaporates from the body even when not sweating, but mechanisms that enhance sweating increase evaporation. As long as skin temperature is greater than its surroundings, radiation and conduction provide heat loss. At very high environmental temperatures, these processes cannot work, and evaporation is the only manner in which heat can be dissipated.

All homeostatic mechanisms use **negative feedback** to maintain a constant value (called the **set point**). **This is the most important point in this topic!** Negative feedback means that **whenever a change occurs in a system, this automatically causes a corrective mechanism to start, which reverses the original change and brings the system back towards the set point (i.e. 'normal')**. It also means that the **bigger** the change the **bigger** the corrective mechanism. Negative feedback applies to electronic circuits and central heating systems as well as to biological systems. When your oven gets too hot, the heating switches off; this allows the oven to cool down. Eventually it will get **too** cold, when the heating will switch back in, so raising the temperature once again.

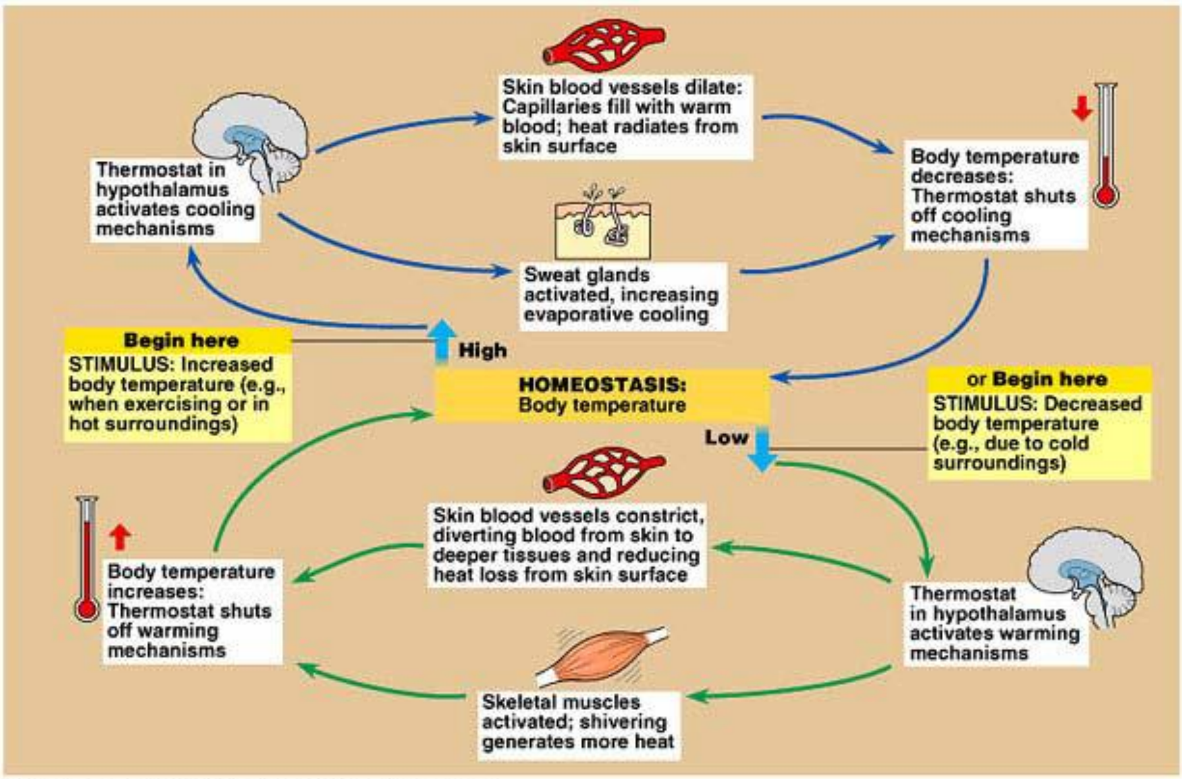
So, in a system controlled by negative feedback, **the set level is never perfectly maintained**, but **constantly oscillates about the set point**. An efficient homeostatic system **minimises** the size of the oscillations. **Some** variation **must** be permitted, however, or both corrective mechanisms would try to operate at once! **This is particularly true in hormone-controlled homeostatic mechanisms** (and most **are**), where there is a significant time-lag before the corrective mechanism can be activated. This is because it takes time for protein synthesis to commence, the hormone to diffuse into the blood-steam, and for it to circulate around the body and take effect.

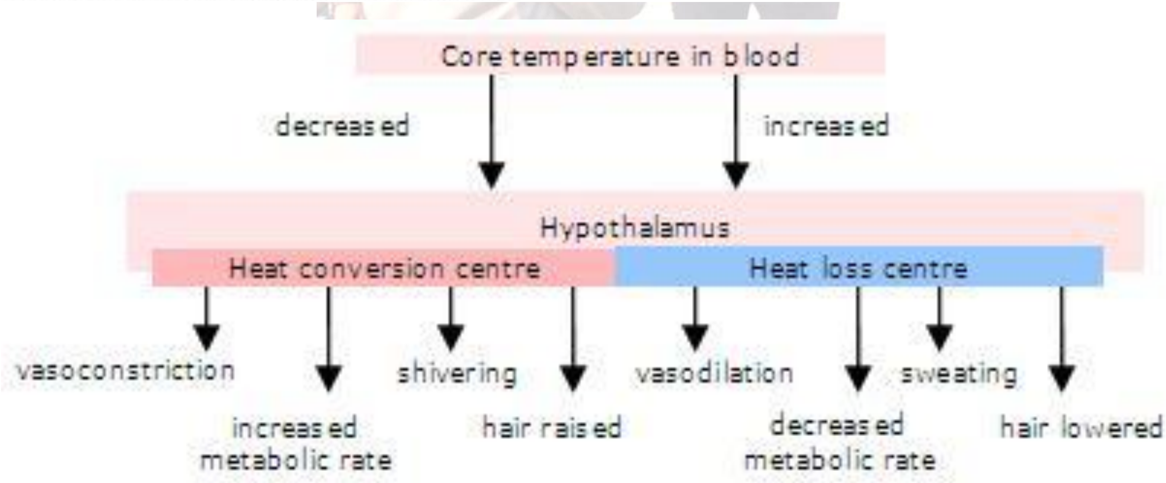
FUNDAMENTAL PROCESSES IN THERMOREGULATION

Skin temperature rises and falls with the temperature of a person's surroundings. However, the temperature of deep body tissues, that is, the core temperature, remains relatively constant at 98.0uF to 98.6uF (37uC). Infact, core temperature normally remains between 97uF and 100uF, even while environmental temperatures fluctuate from as low as 55uF to as high as 130uF.2 This is due to a remarkable thermoregulatory system that is conventionally organized into three components: afferent sensing, central control, and efferent responses.

Temperature Homeostasis (Thermoregulation)

One of the most important examples of homeostasis is the regulation of body temperature. Not all animals can do this physiologically. Animals that maintain a fairly constant body temperature (birds and mammals) are called **endotherms**, while those that have a variable body temperature (all others) are called **ectotherms**. Endotherms normally maintain their body temperatures at around 35 - 40°C, so are sometimes called **warm-blooded animals**, but in fact ectothermic animals can also have very warm blood during the day by basking in the sun, or by extended muscle activity 9e.g. bumble bees, tuna). The difference between the two groups is thus that endothermic animals use **internal** corrective mechanisms, whilst ectotherms use **behavioural** mechanisms (e.g. lying in the sun when cold, moving into shade when hot). Such mechanisms can be **very** effective, particularly when coupled with **internal** mechanisms to ensure that the temperature of the blood going to vital organs (brain, heart) is kept constant. We use **both!**





In humans, body temperature is controlled by the **thermoregulatory centre** in the **hypothalamus**. It receives input from **two sets** of **thermoreceptors**: **receptors in the hypothalamus** itself monitor the temperature of the blood as it passes through the brain (the **core temperature**), and **receptors in the skin** (especially on the trunk) monitor the **external**

temperature. **Both** sets of information are needed so that the body can make appropriate adjustments. The thermoregulatory centre sends impulses to several different effectors to adjust body temperature.

Our first response to encountering hotter or colder condition is **voluntary -** if too hot, we may decide to take some clothes off, or to move into the shade; if too cold, we put extra clothes on - or turn the heating up! It is only **when these responses are not enough** that the **thermoregulatory centre** is stimulated. This is part of the **autonomic nervous system**, so the various responses are all **involuntary**.

When we get **too hot**, the **heat loss centre** in the hypothalamus is stimulated; when we get **too cold**, it is the **heat conservation centre** of the hypothalamus which is stimulated.

Note that some of the responses to low temperature actually **generate heat** (**thermogenesis**), whilst others just **conserve heat**. Similarly some of the responses to cold **actively cool the body down,** while others just **reduce heat production** or **transfer heat to the surface**. The body thus has a range of responses available, depending on the internal and external temperatures.

The exact responses to high and low temperatures are described in the table below:

Effector	**Response to low temperature**	**Response to high temperature**
Smooth muscles in arterioles in the skin.	Muscles contract causing vasoconstriction. Less heatis carried from the core to the surface of the body, maintaining core temperature. Extremities can turn blue and feel cold and can even be damaged (frostbite).	Muscles relax causing vasodilation. More heatis carried from the core to the surface, where it is lost by convection and radiation(conduction is generally low, except when in water). Skin turns red.
Sweat glands	No sweat produced.	Glands secrete sweat onto surface of skin, where it evaporates. Since waterhas a high latent heat of evaporation, it takes heat from the body. High humidity, and tight clothing made of man-made fibres reduce the ability of the sweat to evaporate and so make us uncomfortable in hot weather. Transpirationfrom trees has a dramatic cooling effect on the

		surrounding air temperature.
Erector pili muscles in skin (attached to skin hairs)	Muscles contract, raising skin hairs and trapping an insulating layer of still, warm airnext to the skin. Not very effective in humans, just causing "goosebumps".	Muscles relax, lowering the skin hairs and allowing air to circulate over the skin, encouraging convection and evaporation.
Skeletal muscles	Shivering: Muscles contract and relax repeatedly, generating heat by friction and from metabolic reactions (respiration is only 40% efficient: 60% of increased respiration thus generates heat).	No shivering.
Adrenal and Thyroid glands	Glands secrete adrenaline and thyroxine respectively, which increases the metabolic rate in different tissues, especially the liver, so generating heat.	Glands stop secreting adrenaline and thyroxine.
Behaviour	Curling up, huddling, finding shelter, putting on more clothes.	Stretching out, finding shade, swimming, removing clothes.

The thermoregulatory centre normally maintains a set point of 37.5 ± 0.5 °C in most mammals. However the set point can be altered in special circumstances:

- **Fever**. Chemicals called **pyrogens** released by white blood cells raise the set point of the thermoregulatory centre causing the whole body temperature to increase by 2-3 °C. This helps to kill bacteria, inhibits viruses, and explains why you shiver even though you are hot.
- **Hibernation**. Some mammals release hormones that reduce their set point to around 5°C while they hibernate. This drastically reduces their metabolic rate and so conserves their food reserves e.g. hedgehogs.
- **Torpor**. Bats and hummingbirds reduce their set point every day while they are inactive. They have a **high surface area/volume ratio**, so this reduces heat loss.

Extra Important Information's

Body–environment exchange

Over time, heat gains and losses must balance to maintain homeothermy – maintaining the body's core temperature within its narrow range. Temperatures encountered by humans.

Heat gains

Most of the body's heat production is in the liver, brain, and heart, and in the skeletal muscles during exercise. This heat is transferred, through the network of blood vessels and tissue, to the skin, from whence it is lost to the environment. The amount of metabolic heat generation depends on the level of muscular exercise, and to a lesser degree on factors such as illness and time in the menstrual cycle. A base level of metabolism has been defined as the metabolism of a seated person resting quietly. For a man of typical height and surface area, this amount is about 100 W. To normalize among people of different sizes, metabolism is typically expressed in per unit skin surface area. A specialized unit, the 'met', has been defined in terms of multiples of basal metabolism. Brain metabolism consists mostly of the energy required to pump ions through neuron cell membranes (Guyton and Hall, 2000). This takes place at a rate per unit mass that is 7.5 times that of non-nervous system tissues. Although the brain only comprises 2% of the body mass, it produces about 15% of the body's total metabolism. During high mental activity, this neuron metabolism can more than double. The head has specialized thermoregulatory physiology to assure the high rates of heat loss needed to keep the brain temperature constant. Heat may also be gained from the environment through the skin. Solar radiation, and long-wave radiation from surfaces warmer than skin temperature, warm the skin as a function of its color and surface emissivity. Although in most conditions convection and evaporation carry metabolic heat away from the body, hot winds may cause the skin to warm, when the body's sweat supply rate is insufficient to keep up with evaporation, and sensible gains exceed evaporative losses.

Heat Losses

The body's heat losses are through radiation, convection, conduction, evaporation, and through respiration. Figure 16.2 shows heat transfers above and below the skin surface. In a neutral environment, where the body does not need to take thermoregulatory action to preserve its balance, evaporation provides about 25% of total heat loss, and sensible heat loss provides 75%. During exercise, these percentages could be reversed. In general, the heat transfer by conduction through the soles of the feet or to a chair is small, around 3%. In normal indoor environments with still air, the convective and radiation heat transfer are about equal (McIntyre and Griffiths, 1972).

Thermal regulation

Thermoregulation generally refers to four mechanisms: sweating, shivering, vasodilatation, and vasoconstriction. Sweating increases body heat loss by increasing sweat evaporation. Shivering produces heat by involuntary movement of muscle. Vasodilatation and vasoconstriction refer to changes in blood vessel diameter, which affect skin temperature by changing the rate of blood exchange with the interior. In the heat, increased conductance below the skin surface (due to increased blood flow) facilitates heat transfer from body interior to the skin. Then convection and evaporation of sweat carries the heat away from the surface of the body to the environment. In the cold, muscle tensing and shivering increase heat production and body temperature.

Decreased conductance (due to decreased blood flow) keeps the heat from escaping to the cold environment. This combination of heat loss and heat gain control mechanisms is able to maintain human body core temperature within a very small range in spite of variation in metabolic output that can exceed an order of magnitude above the base value, and similar variation in the heat loss rate from body to the environment.

A comprehensive overview of the thermoregulatory control system is found in Guyton and Hall (2000) and Gagge and Gonzalez (1996). The control system senses the body's thermal state with sensory organs in the hypothalamus (within the brain), within the skin, and in the spine and some abdominal organs. The thermal sensors within the anterior hypothalamus sense the core temperature of the body, especially that of the brain, by measuring the temperature of blood passing through it. The anterior hypothalamus's warm sensors outnumber its cold sensors by three to one, and are most active when the body core is too hot. The anterior hypothalamus primarily acts as a controller of the body's heat loss; any rise in hypothalamus temperature above its set point causes it to send out nerve impulses to activate vasodilatation and sweating, the body's heat loss mechanisms. The mechanism is precise: the setpoint for vasodilatation and sweating is only two tenths of a degree higher than the 37°C set point for vasoconstriction, and the setpoint for shivering is just below 36 °C (Sessler, 2006). These setpoints are raised during exercise or fever. The skin temperature also plays a secondary role in controlling cooling in the heat: at the same core temperature, a warmer skin temperature enhances the sweat rate, and a colder skin inhibits it (Stolwijk *et al.*, 1971; Nadel *et al.*, 1971).

Cold- and warm-sensitive nerve endings located in the skin send signals, through the sympathetic nerve system to the anterior hypothalamus, that are passed on to the posterior hypothalamus, which acts a controller of body temperature during cold. The skin has many (ten times) more cold sensors than warm, and the cold sensors are closer to the surface than the warm, so these peripheral sensors are more dedicated to the rapid detection of cold than of warmth. There are some cold-sensitive temperature sensors in the anterior hypothalamus, and in the spine and abdomen, that also alert the posterior hypothalamus to body cooling. The posterior hypothalamus emits nerve signals to the periphery, stimulating vasoconstriction and shivering, and it also initiates the release from the medulla of hormonal messengers such as norepinephrine that rapidly initiate vascular contraction throughout the body.

If a local part of the body is warmed or cooled, sweating or vasoconstriction can be locally initiated and controlled for that particular area, even if the rest of the body is being centrally controlled for a different temperature. The relative contributions to sweating from core and skin temperatures are about 10 to 1 (Nadel and Stolwijk, 1973; Nadel *at al*., 1971; Benzinger *et al*., 1961). The core threshold for sweating decreases by 0.6 °C as the skin temperature is warmed from 29 °C to 33 °C. Similarly, with the hypothalamus temperature constant, heating a local body part can induce local sweating (Nadel *et al*., 1971; Randall, 1946).

Thermoreceptors

Human beings can perceive different levels of cold and warmth (including pain) through four discrete types of sensory organs – cold, warmth, and cold and hot pain receptors (Guyton and Hall, 2000; Craig, 2003). The relative degrees of stimulation of the nerve endings determine the person's perception of the intensity of thermal sensation. When touched with small (punctate) warm and cold stimulators, some spots on the skin feel warm and/or cold, others do not. Each receptor is activated in a specific range (Fig. 16.6). At high temperatures perceived as painfully hot, warmth receptors are inactive, and pain receptors are simulated. The same is true for painfully cold temperatures. If a warm stimulus is applied to a cold thermoreceptor, no signal is produced. Thermoreceptors are located mainly in the skin and in the hypothalamus, but are also found in places such as the spinal cord, abdominal viscera, and in or around the great veins in the upper abdomen and thorax.

Evaporative control systems

Because the temperature gradient between the skin surface and the environment diminishes in hot weather, sensible heat transfer becomes insufficient to remove the body's metabolic heat. Evaporation of body moisture is a highly efficient heat removal process, and therefore complex physiological mechanisms have evolved to encourage evaporation under conditions of heat stress, and to minimize it when not, both to avoid overcooling and to minimize the amount of water lost by the body.

Thermoregulatory sweating mechanism

The body's eccrine sweat glands primarily serve the purpose of thermoregulation, although emotions can also stimulate them. When the body becomes overheated, sweat is secreted onto the surface of the skin and is evaporated by the heat supplied by the skin surface. If the atmosphere is dry, evaporation is effective, and high sweat rates can occur without wetting much of the skin around the sweat gland opening, so sweating may not be perceived. If the atmosphere is moist, the sweat-covered area around the sweat gland must increase in order to evaporate the quantity of sweat coming out of the gland. The term ‘skin wettedness’ alludes to this area.

Eccrine sweat glands are regulated by the autonomic nervous system. For thermoregulation, they are activated through nerve fibers that stimulate the release of the neurotransmitter acetylcholine. Warming in the anterior area of the hypothalamus excites sweating through the whole body.

Acclimatization and sweat dripping

People are born with a considerable excess of sweat glands, but if they do not spend their early years in a hot climate, many of the glands become permanently inactive. Whether or not people live in hot climates, accumulated exposure to heat or exercise (acclimatization) will cause more of their available sweating glands to be active, so that their sweat more evenly covers their bodies, making their evaporative heat loss more effective (Kuno, 1956; Guyton and Hall, 2000). In the heat, if sweat beads up and drops off the skin, it normally means that the person is not well acclimatized.

Emotional sweating

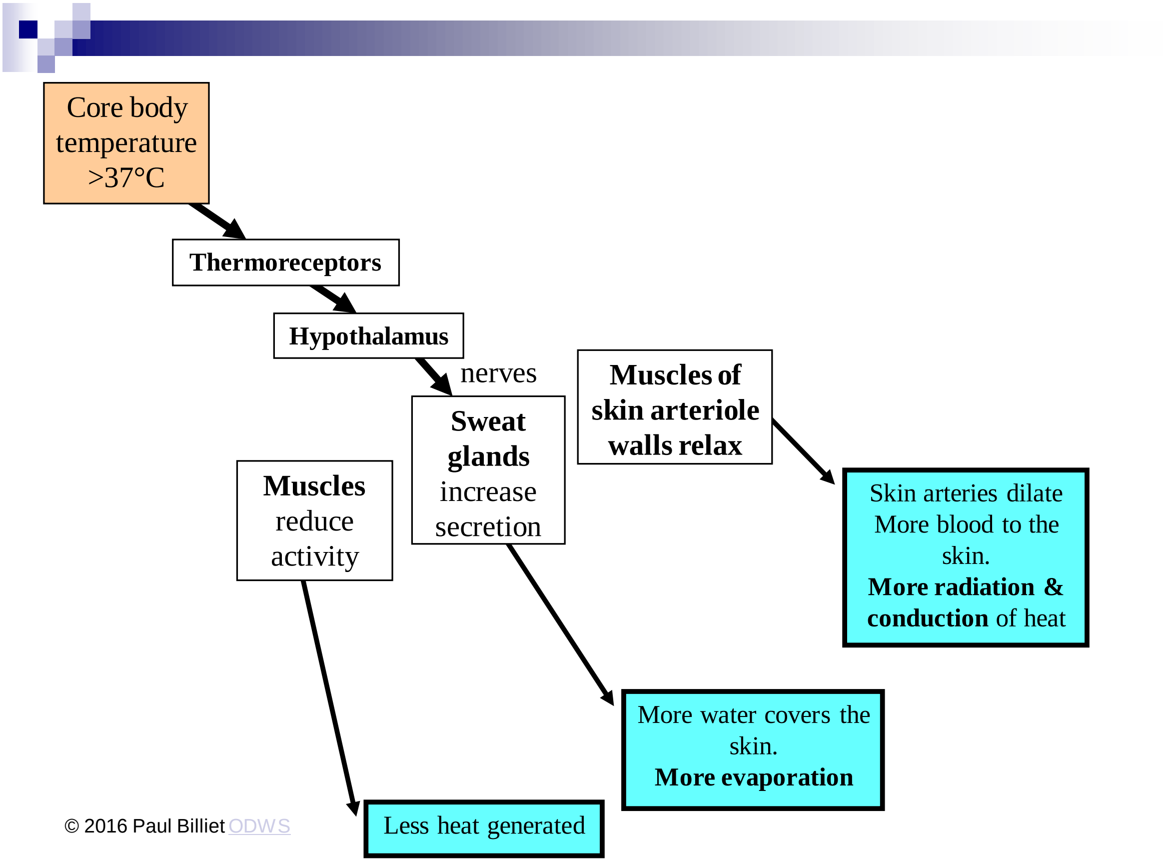
The palms of hands and soles of feet have a large number of eccrine sweat glands, but these do not respond during thermal stimulation or play a substantial role in thermoregulation. They do, however, sweat profusely as a result of emotional excitement and strong mental activity (Kuno, 1956). The sweat glands on palms and soles are stimulated by epinephrine or norepinephrine circulation in the blood. This emotional sweat starts and stops very rapidly, and the resulting changes to electrical resistance of the skin (galvanic skin response) are exploited by lie detectors to detect psychological stress.

Conduction

Conduction takes place primarily to solid surfaces in the environment, since conduction from the skin surface to fluid or gaseous surroundings is rapidly replaced by convective processes. A standing person has roughly 3% of his/ her body surface area in contact with the floor. For a seated or reclining person, the surface contact area to the seat or bed is in the order of 8 to 12% of total body surface area, depending on how yielding the contact surface is. The overall heat transfer from the body via conduction is usually less than these percentages suggest, because the conductivity of bedding and seating materials tends to be small. However, if the contact surface conductivity is high (such as the earth), conduction can be a dominant path of heat exchange with the environment.

Shivering

In cold environments, the body first conserves its internal temperature by vasoconstricting its blood vessels. If this passive insulative measure proves insufficient, the body begins to actively generate additional metabolic heat through tensioning its muscles, starting with 'muscle tone' in the skin, and then leading to involuntary shivering. Shivering can raise metabolic heat production by as much as three times the normal sedentary value. It begins in the trunk region and spreads to the limbs (Spurr *et al*., 1957).



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