Title
The skin's role in human thermoregulation and comfort

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The skin's role in human thermoregulation and comfort

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16.1 Introduction

This chapter is intended to explain those aspects of human thermal physiology, heat and moisture transfer from the skin surface, and human thermal comfort, that could be useful for designing clothing and other types of skin covering.

Humans maintain their core temperatures within a small range, between 36 and 38°C. The skin is the major organ that controls heat and moisture flow to and from the surrounding environment. The human environment occurs naturally across very wide range of temperatures (100 K) and water vapor pressures (4.7 kPa), and in addition to this, solar radiation may impose heat loads of as much as 0.8 kW per square meter of exposed skin surface. The skin exercises its control of heat and moisture across a 14-fold range of metabolisms, from a person's basal metabolism (seated at rest) to a trained bicycle racer at maximum exertion. The skin also contains thermal sensors that participate in the thermoregulatory control, and that affect the person's thermal sensation and comfort.

The body's heat exchange mechanisms include sensible heat transfer at the skin surface (via conduction, convection, and radiation (long-wave and short-wave)), latent heat transfer (via moisture evaporating and diffusing through the skin, and through sweat evaporation on the surface), and sensible plus latent exchange via respiration from the lungs. Dripping of liquid sweat from the body or discharge of bodily fluids cause relatively small amounts of heat exchange, but exposure to rain and other liquids in the environment can cause high rates of heat loss and gain.

Clothing is used outside the skin to extend the body's range of thermoregulatory control and reduce the metabolic cost of thermoregulation. It reduces sensible heat transfer, while in most cases permitting evaporated moisture (latent heat) to escape. Some clothing resists rain penetration, both to prevent the rain from directly cooling the skin, and to prevent the loss of insulation effectiveness within the clothing. Wet clothing will have a higher heat transfer than dry: depending on design, it can range from almost no difference to a 20-fold increase. Clothing is nearly always designed to allow the wearer's breath to enter and exit freely in order to keep the temperature and humidity of inhaled air low, and to avoid moisture condensation within the clothing.

Bedclothes are a form of clothing used for sleeping. Because the metabolic rate during sleep (0.7 met) is lower than the basal rate, and the body's skin temperature tends to be higher during sleep, bedclothes typically have a higher insulation value than clothing.

Bandages and other medical coverings may also be a special case of clothing, controlling the heat, moisture, and biotic transfer above a damaged skin.

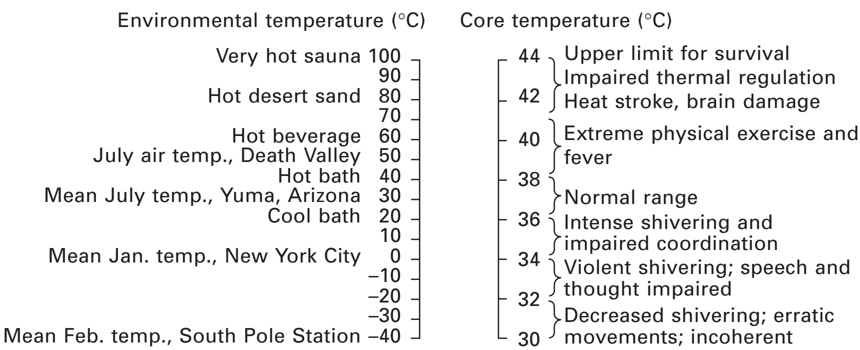
This chapter gives a brief description of the body's skin structure and thermoregulatory system, followed by a more detailed description of how heat and moisture are transferred at the skin's outer boundary, and finally, the comfort implications of skin temperature and humidity. Since skin characteristics are not evenly distributed across the surface of the entire body, it is useful for clothing design to have this information presented by individual body part, wherever possible.

16.2 Body–environment exchange

Over time, heat gains and losses must balance to maintain homeothermy – maintaining the body's core temperature within its narrow range. Figure 16.1 illustrates the full range of core temperatures and environmental temperatures encountered by humans.

16.2.1 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



16.1 Ranges of environmental and human body temperatures (adapted from Brooks *et al.*, 1996).

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.

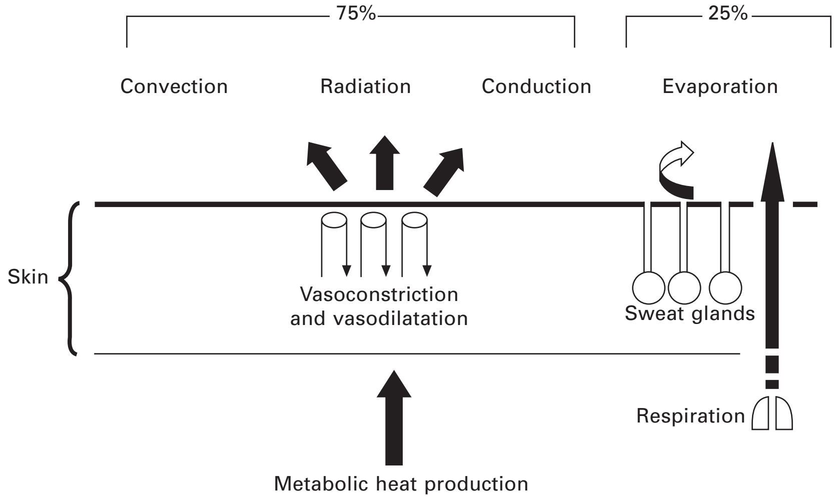
To normalize among people of different sizes, metabolism is typically expressed in per unit skin surface area. A specialized unit, the 'met', has been defined in terms of multiples of basal metabolism: 1 met is 58.15 W/m^2. A sleeping person has a rate of 0.7 met, and reclining awake is 0.8 met. Office work is 1.2 met: a mostly seated activity but one that involves occasional moving about. Walking slowly (0.9 m/s, or 2 mph) is 2 met, moderate walking (1.2 m/s or 2.7 mph) is 2.6 met, and fast walking (1.8 m/s or 4 mph) is 3.8 met (*ASHRAE Handbook of Fundamentals*, 2005). Swimming ranges from 4 to 8 met, and jogging 8 to 12 met (Brooks *et al.*, 1996). The work efficiency of muscles is about 15%, with 85% of total energy released as heat.

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.

16.2.2 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). In the



16.2 Heat transfer through and above the skin.

outdoors, wind strongly affects convective heat loss or gain, and radiation (solar and long-wave) can also cause large losses and gains. These forces act asymmetrically on the body, affecting some parts more than others.

16.2.3 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).

16.3 Skin

16.3.1 Skin surface area

The area of skin on the body can be estimated from the body's height and weight, using a relationship developed by DuBois and DuBois (1915):

$$A_{Dubois} = 0.202\ M^{0.425}\ L^{0.725}\,\mathrm{m}^2 \qquad [16.1]$$

where A_{Dubois} is the skin area in m^2, M is the mass in kg, and L the person's height in m. A 1.65 m person weighing 73 kg will have a skin surface area of 1.8 m^2, a commonly used figure for 'standard' men. The range of surface areas from school-age children through large adults is 0.8 through 2.4 m^2.

The surface areas of local body segments vary among individuals, but it can be useful to know the relative percentages of total surface area that they cover. Table 16.1 presents such percentages for a detailed female thermal manikin with a total surface area of 1.588 m^2.

16.3.2 Skin structure

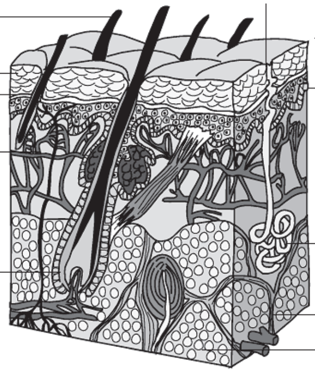
The skin provides a first barrier between the organism and its environment. It keeps the uncontrolled loss or gain of water through the skin at a low constant level. In addition to that, it contains complex vascular systems and sweat glands that allow it to change its conductance in response to thermoregulatory demands of the body. It also contains four types of thermally-sensitive nerve endings (to cold, warmth, and hot and cold pain) that sense the skin's temperature and transmit the information to the brain.

Although there are some regional variations in skin thickness, in most places the skin is about 2 mm thick. It includes two main layers, the epidermis and dermis (Fig. 16.3).

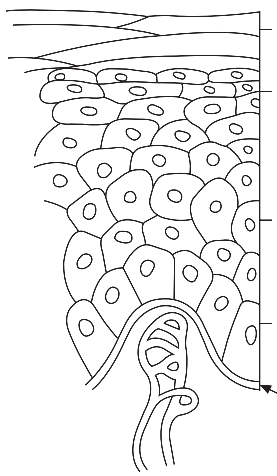
The epidermis is thin, mostly about 0.075–0.15 mm (except for the soles and palms, which are thicker). The outermost layer of the epidermis is the

Table 16.1 Body surface areas for a detailed female thermal manikin

Body part	Area (m^2)	Percentage (%)
Head	0.117	7.5
Chest	0.143	9.2
Back	0.135	8.6
Pelvis	0.143	9.2
L-Upper arm	0.093	5.9
R-Upper arm	0.093	5.9
L-Lower arm	0.063	4.1
R-Lower arm	0.063	4.1
L-Hand	0.039	2.5
R-Hand	0.039	2.5
L-Thigh	0.143	9.2
R-Thigh	0.143	9.2
L-Calf	0.125	8.0
R-Calf	0.125	8.0
L-Foot	0.048	3.1
R-Foot	0.048	3.1
Whole-body	1.588	100



16.3 Cross-sectional view of the skin (Image courtesy of LifeART.com).



16.4 Layers of the epidermis (Copyright (2004) from *Skin, Hair and Nails: Structure and Function* by Forslind and Lindberg, Reproduced by permission of Routledge, Taylor and Francis Group LLC).

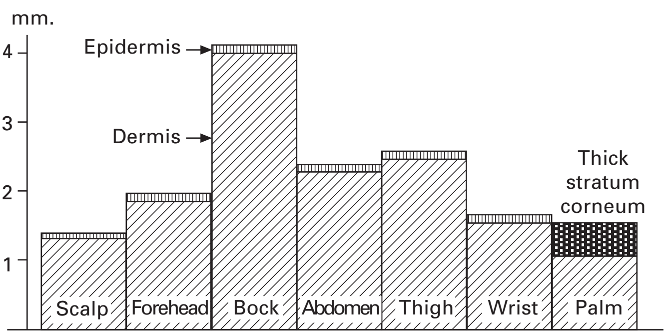
stratum corneum (Fig. 16.4), an assemblage of overlapping plate-like cells (corneocytes), interleaved with hydrophobic layers of lipids. The stratum corneum is 0.01 to 0.1 mm thick, and serves as the skin's primary barrier to water diffusion. Because the corneocytes are impervious to water transmission, whatever moisture passes the stratum corneum barrier has to travel around them through the lipids, following a long tortuous path back and forth among the plates. The stratum corneum is well described in Forslind and Lindberg (2004), who make the memorable point in their introduction that this waterproof barrier protecting our bodies is thinner than the plastic cling wrap used to protect our sandwiches.

The corneocytes are non-viable, having lost their nucleus and organelles. They are continuously shed from the surface as they are replaced from below. The shedding is accomplished by the dissolution of small rivetlike structures called desmosomes that hold the plates together. The dissolution is mediated by enzymes controlled by the moisture gradient in the stratum corneum layer. Corneocytes consist of a protein cell wall and a matrix of keratinous fibrils within, which stiffen the structure. When immersed in water or exposed to high levels of atmospheric humidity, they absorb moisture and thicken by as much as 25%; this is thought to smooth the outer skin surface and protect it from tearing when wet (Forslind and Lindberg, 2004).

Below the stratum corneum, at the bottom of the epidermis, is a basal layer of stem cells ('stratum basale'), which generates epidermal cells continuously. Above it are two layers in which the upward-migrating cells transform themselves into the interleaved plates and lipids of the stratum corneum. The basal level has an undulating lower contour to provide mechanical shear resistance, connecting the epidermis to the dermis layer below it.

The dermis is much thicker than the epidermis, varying by body part (Fig. 16.5, Rushmer *et al.*, 1966). It contains vascular systems, sweat glands, and thermoregulatory nerves at different depths in the layer. These will be described in the following sections. The dermis also houses nail and hair follicles, which produce keratinized structures physiologically related to the stratum corneum. Sebaceous glands within the dermis serve the functions of smoothing and moisture-proofing the outer surface of the skin, and coating hair to reduce tangling.

Beneath the dermis lies the subcutaneous or fat layer, whose thickness is highly variable among individuals (for a normal person, it is, on average,



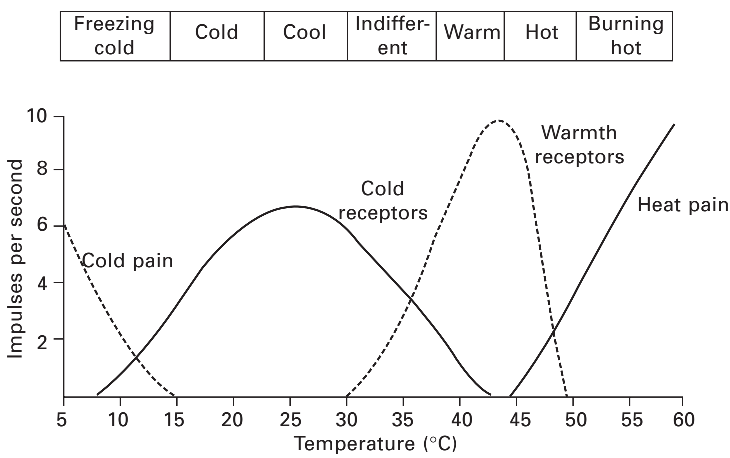
16.5 Regional variations in thickness of skin (From Rushmer *et al.*, 1966, with permission from the American Association for Advancement of Science, Washington, D.C.).

about 17 times the thickness of the dermis – Stolwijk and Hardy, 1965). It serves the functions of insulating the underlying musculature against conductive heat transfer to the outer skin, as well as of storing food energy for the body.

16.3.3 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.

The discovery of discrete thermoreceptors was made independently in 1884/1885 by Blix in Sweden, Goldscheider in Germany, and Donaldson in America. All three investigators, and many since, have reported that, 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.



16.6 Discharge frequencies of a cold receptor, a warmth receptor, and cold and hot pain nerve fibers at different temperatures (From Guyton and Hall, 2000: *Textbook of Medical Physiology*, with permission from W.B. Saunders Company, Philadelphia).

The thermoreceptors are located in the dermis at an average depth of 0.15 to 0.17 mm for cold receptors and 0.3 to 0.6 mm for warmth receptors (Bazett and McGlone, 1930; Bazett *et al*., 1930; Hensel, 1982). These depths indicate that the layer of cold receptors is immediately beneath the epidermis, and the site of warmth receptors is within the upper layer of the dermis. The number of cold thermoreceptors far exceeds the number of warmth receptors. In general, there are about ten times more cold receptors than warmth receptors in skin (Guyton and Hall 2000). The distribution of the cold and warm receptors is shown in Table 16.2. Figure 16.7 displays examples from classic studies: the warm and cold receptors on the dorsal forearm (Strughold and Porz, 1931), and warm receptors on the fingers (Rein, 1925).

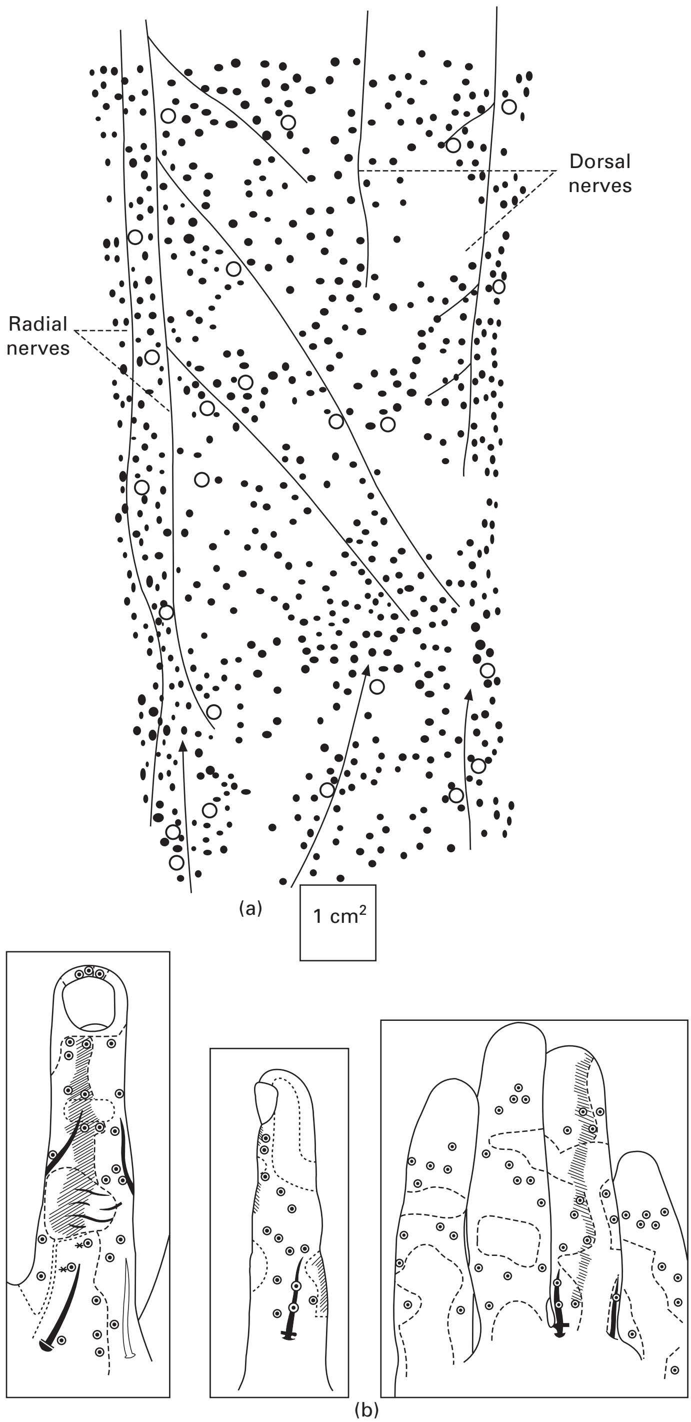
The preponderance of cold spots over warm spots, and the shallower depth of cold spots relative to the skin surface, suggest that humans are more sensitive to danger from cold than from heat.

The dynamic characteristics of thermoreceptors determine thermal sensation and comfort responses. A thermoreceptor is capable of a great deal of adaptation. When it is subjected to an abrupt change in temperature, it is strongly stimulated at first, sending impulses at a high frequency, but this stimulation fades rapidly during the first minute following the temperature change, and then progressively more slowly until it reaches a steady level (Fig. 16.8 – Hensel, 1982). Thermoreceptors respond to steady temperature states at this lower rate. A person feels much colder or warmer when the temperature of the skin is actively falling or rising than when the temperature remains at the same

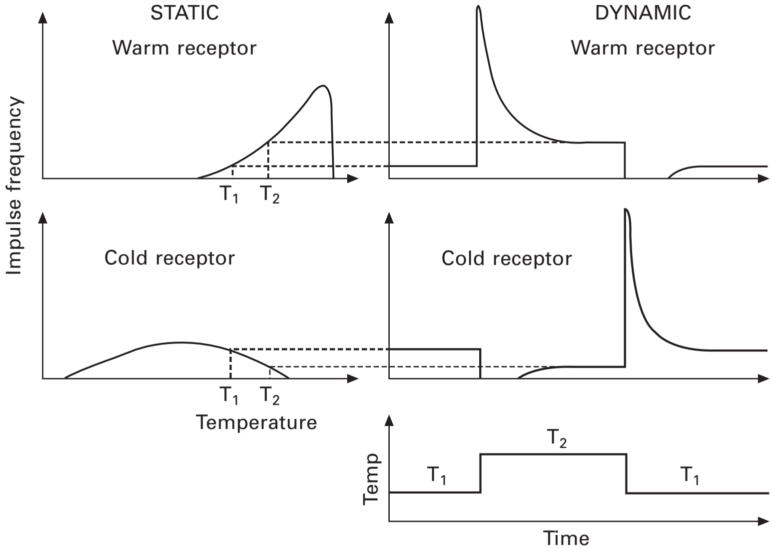
Table 16.2 Number of cold and warm spots per cm^2 in human skin

Body parts	Cold spots (Strughold and Porz 1931)	Warm spots (Rein 1925)
Forehead	5.5–8	
Nose	8	1
Lips	16–19	
Other parts of face	8.5–9	1.7
Chest	9–10.2	0.3
Abdomen	8–12.5	
Back	7.8	
Upper arm	5–6.5	
Forearm	6–7.5	0.3–0.4
Back of hand	7.4	0.5
Palm of hand	1–5	0.4
Finger dorsal	7–9	1.7
Finger volar	2–4	1.6
Thigh	4.5–5.2	0.4
Calf	4.3–5.7	
Back of foot	5.6	
Sole of foot	3.4	

Adapted from Hensel, 1982



16.7 (a) Warm and cold receptors on the dorsal forearm, and (b) warm receptors on the fingers.



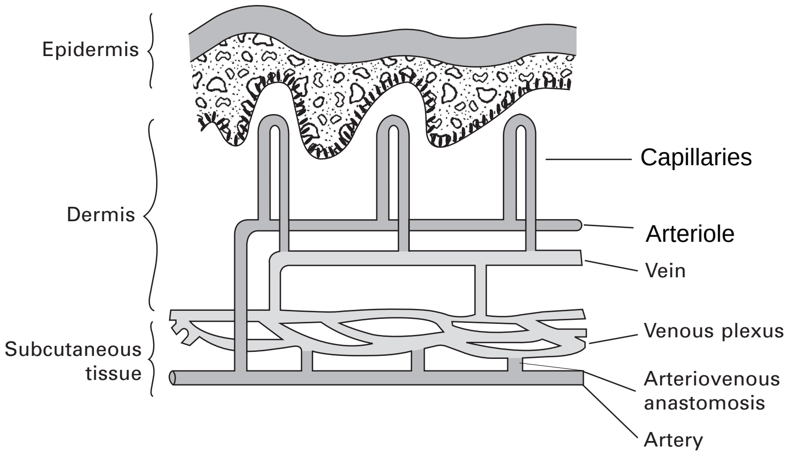
16.8 General properties of thermoreceptors. Static and dynamic responses of warm and cold receptors to constant temperature and temperature changes (From Hensel, 1982: *Thermal Sensation and Thermal Receptors in Man*, courtesy of Charles C Thomas Publishers, Springfield, Illinois.).

level. This explains the stronger sensation of coolth or warmth felt upon entering a cold pool or a hot tub. The overreaction during transient exposures has been termed 'overshoot' (deDear *et al*., 1993; Gagge *et al*., 1967; Zhang, 2003). The dynamic response of thermoreceptors to changes in temperature in essence predicts the body's steady-state response to a new thermal environment well before the body's heat content has had time to alter significantly. Such a capability has clear adaptive value for survival.

16.3.4 Vascular system

Figure 16.9 illustrates the vascular system in the skin. The primary function of blood circulation is to deliver nutrients and oxygen to tissues and organs. In addition to that, blood circulation assists the principal mechanisms of thermal homeostasis. It keeps the heat within the body when it is cold by reducing blood circulation (vasoconstriction) to the skin, or enhances the outward flow of heat to the skin by vasodilatation.

In the outer region of the skin (epidermis and outer dermis), the thermal resistance of the tissues determine heat flow, and the variation of blood flow within the small dermal capillaries is not thermally important. Below these, however, the subcutaneous region contains the venous plexus, a dense vascular network that strongly affects skin temperature and heat transfer from the



16.9 Vascular system in the skin (From Guyton and Hall, 2000: *Textbook of Medical Physiology*, with permission from W.B. Saunders Company, Philadelphia, p 823, with permission from Elsevier).

skin to the environment. Blood flow into the venous plexus is fed by arterioles, which vasodilatate and vasoconstrict significantly. Since blood flow varies to the fourth power of vessel diameter, a doubling in diameter corresponds to a 16-fold increase in the blood supply volume. In cold, the blood supply to the venous plexus can be effectively as low as zero, resulting in a local gradient across the skin of 10 K. In heat, dilatation can cause an eight-fold increase in the skin conductance, producing a gradient from the body's central core temperature to skin surface temperature that is less than 1 K.

Vascular control takes place through the sympathetic nervous system. When stimulated in the posterior hypothalamus or skin, the rate of nerve impulses transferred to the periphery activates vasoconstriction or vasodilatation. The relative contributions to the control signal from the hypothalamus (core) temperature and from the skin temperature are in the order of 10:1, so the system is heavily weighted toward representing the overall body thermal state.

Highly exposed areas of the body, such as the fingers, hands, feet, and ears, have an additional vascular control mechanism that can vary their temperature and heat loss across a wide range. Arterio-venous anastamoses (AVAs) (Sherman, 1963) are present in these areas in large numbers. These are valves that, when open, shortcut the normal route of the blood from the arterioles to the venous plexus. The diameters of AVA are 20–150 μm, about 20 times larger than that of capillaries (1–8 μm) and five times larger than that of arterioles (15–30 μm) (Hales, 1984, 1985). When the body is hot, AVAs are stimulated by sympathetic nerves to open and rapidly supply arterial blood to the venous plexus, which acts as a warm reservoir close to the skin surface. This promotes heat loss by conduction through the overlying tissues to the surroundings.

Warm-blooded animals keep their core temperature fairly constant using another important vascular feature: counter-current heat exchange between arteries and veins, where the warm outbound arterial blood transfers heat to the cold inbound venous blood. The counter-current vascular structures can be categorized into three types. The first has one artery and one vein in parallel, as exist down the lengths of our arms and legs, and in most birds' legs. The second has one artery surrounded by many veins, as in human fingers and relatively uninsulated body parts such as whales' fins and some animals' tails. The third consists of a net where 20–40, or sometimes several hundred, small arteries and veins run parallel and are intermingled (Schmidt-Nielsen, 1972). An example of this is the *rete mirabile*, found between the nasal passages and the brain of non-sweating animals like dogs, which rely on panting for keeping their brains cool.

Unlike tissues in other body parts, the brain stores very small amounts of energy and oxygen. Due to the high level of metabolic rate of neurons, the brain needs second-by-second delivery of glucose and oxygen from the blood (Guyton and Hall, 2000), a relatively constant blood flow, 750 ml/min, about 13–15% of the total cardiac output. Since this amount cannot be reduced, the head does not have a vasoconstriction mechanism. If the body is cooling in a cold environment, the head should be wrapped in order to protect it from excessive heat loss. In heat, selective brain cooling (SBC, discussed below under evaporative cooling systems) is able to keep the brain temperature lower than the nearby core temperatures measured in the esophagus (Cabanac, 1993).

16.3.5 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.

Insensible evaporative heat losses

There is always a constant amount of trans-epidermal loss of water vapor directly diffused through the skin, resulting in heat loss by 'insensible evaporation'. In addition, the breathing cycle involves humidifying exhaled air, producing another evaporative heat loss. The transdermal moisture diffusion is about 100 to 150 mL per day per m^2 of skin surface, representing a heat loss 6% as great as the evaporation from a fully wetted surface. The respiratory portion of the body's total heat loss is estimated as 8%, depending on the metabolic rate. Although both these modes of evaporation contribute to heat loss from the body, neither is controlled for the purpose of temperature regulation.

Thermoregulatory sweating mechanism

The body's eccrine sweat glands primarily serve the purpose of thermoregulation, although emotions can also stimulate them. Figure 16.3 shows an eccrine sweat gland and its opening onto the skin surface. 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. It is the fraction of the skin covered with water that would account for a total amount of observed evaporation (ASHRAE Fundamentals, 2005). Perspiration as secreted has a lower salt concentration than interstitial body fluid or blood plasma. Over short intervals of sweating, sweat evaporates indistinguishably from water (Kerslake, 1972; Berglund and McNall, 1973). With extended sweat evaporation, salt may accumulate on the skin, reducing the sweat's vapor pressure and evaporative efficiency. However, this is somewhat offset by the sweat glands reducing the salt concentration of sweat after prolonged heat exposure, presumably to conserve salt.

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. However, as mentioned in Section 16.2.3, the threshold of the hypothalamus temperature for sweating is somewhat modified by skin temperature (Nadel *et al.*, 1971; Benzinger, 1961).

An increase in sweat production is brought about by both increasing the number of participating sweat glands and by increasing the output of each active gland. The primary response to heating a local skin area is to increase the output of individual glands, rather than stimulating a larger number of glands to sweat (Randall, 1946, 1947). Sweat does not begin simultaneously all over the body. On the onset of sweating, the first area is generally the forehead, followed in order by the upper arms, hands, thighs, feet, and back and abdomen (Houdas and Ring, 1982); a little different order is presented by McIntyre (1980) after Kuno (1956) and Randall (1946). The high skin temperature and small number of sweat glands on the zygomatic and buccal regions of the face have been hypothesized to help the evaporation of sweating droplets running down over these regions from the forehead (Randall, 1946).

With repeated intermittent heat exposure, the set point for the onset of sweating decreases and the proportional gain or temperature sensitivity of the sweating system increases (Hensel, 1982). This is acclimatization, and it takes place over a time period of about a week. However, under long-term exposure to hot conditions, the sweating set point increases, perhaps to reduce the physiological effort of sweating.

Sweat gland distribution

The distribution of eccrine sweat production across the body is described in Kuno (1956) and is shown in Table 16.3.

The average density of active glands is around 125–200 glands/cm^2, depending on the individual (Kuno, 1938; Randall, 1946), although considerable variation exists in different areas of the body (Randall, 1946). Table 16.4 gives the sweat gland distribution in various areas.

Table 16.3 Distribution of eccrine sweat production

	Body parts
Greatest	Forehead, neck, back of hand and forearm, back and front of trunk
Middle	Cheeks, arms and legs, lateral surface of trunk
Least	Inside of thighs, soles, palms, armpits

Kuno, 1956

Table 16.4 Sweat gland distribution

Segment	Sweat glands (functional pores/cm^2)
Forearm, extensor surface	213
Upper arm, over biceps	177
Dorsum of hand	377
Trunk – anterior chest	151
Trunk – scapular region of back	30
Leg (over gastrocnemius)	99
Thenar eminence	284
Face – forehead	167
Face – zygomatic arch (temple)	21
Face – buccal (cheek, jaw)	16

Adapted from Randall, 1946

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. An acclimatized person, in fact, looks drier, even though the sweat rate may be greater. Dripping sweat is adaptively undesirable because it provides no evaporative cooling to the skin while dehydrating the body.

The maximum sweat rate for an unacclimatized person seldom reaches 1 liter/hour. However, a well-acclimatized person can sweat as much as 2–3 liter/hour, which, when evaporated, removes about ten times the basal body heat production. It is equivalent to a 4–6 pounds of body weight loss per hour (Guyton and Hall, 2000). The concentration of sodium chloride in the sweat is also smaller for an acclimatized person.

Hidromeiosis

When a local area of skin is thoroughly wet for periods exceeding two hours, the sweat rate abruptly drops off, an effect called 'hidromeiosis' (Sargent, 1961; Hertig *et al*., 1961; Candas *et al*., 1980). It can be brought on by a large amount of unevaporated sweat on the skin surface, or by exposure to very high ambient humidities (such as produced by waterproof coverings over the skin). If the skin is dried (by a towel, wicking fabric, or by convection), the sweat-rate dropoff is rapidly reversed. The causal mechanism has been the subject of debate for many years and has not yet been resolved. Proposed mechanisms include squeezing the sweat pores by swelling in the epidermal cells, changes in the water/salt balance around the sweat glands affecting the secretion rate, and changes in the transmission of nerve impulses at the junction between nerve and gland. Because a fully wetted skin surface cannot further increase its evaporative heat removal rate, and is likely to be experiencing sweat drip, the hidromeiosis mechanism has adaptive benefit to the body by reducing unproductive (in heat removal terms) water loss (Ogawa *et al*., 1984).

Salt will accumulate on the surface of the skin as the water in sweat evaporates. Salt lowers the vapor pressure of water and thereby reduces its evaporation rate. Accumulated salt therefore results in increased skin wettedness for a given rate of evaporative cooling. The *ASHRAE Handbook* (2005) suggests that some of the pleasure of washing after a warm day comes from the restoration of a hypotonic sweat film and decreased skin wettedness.

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.

Apocrine sweat glands

There is another type of sweat gland, the apocrine. The apocrine glands in humans are mainly located in the armpits and pubic region, always exiting to the skin surface via hair follicles. They are stimulated by adrenergic nerves, part of the sympathetic nervous system. Apocrine sweat contains a mixture of substances unlike that of the more watery eccrine sweat (Goldsmith, 1991); the decomposition this mixture by bacteria in the skin creates its odour (McIntyre, 1980). Due to their locations on the body, apocrine sweat glands serve little thermoregulation purpose. Guyton and Hall (2000) suggests that apocrine sweat, together with sebum exiting from the hair follicles, serves a lubrication function in these areas of the body where skin surfaces touch each other.

Selective brain cooling

The brain, with its high rate of internal heat production, needs to be kept cool within a narrow range to avoid damage. The lack of vasoconstriction in the scalp blood vessels has already been noted. Brain temperature, as measured on the tympanum (inner ear), is typically higher than or equal to other core temperatures in the cold, but in the heat, a mechanism called selective brain cooling (SBC) keeps it lower than the other core temperatures (Caputa and Cabanac, 1988). SBC cooling occurs through upper airway respiration and high heat losses from the surfaces of the head, via convection, radiation, and sweating. Sweating from the surface of the head is maintained at the expense of warming the rest of the body: in mild hyperthermia with the body mildly dehydrated, the sweat rate on the trunk will be depressed while remaining constant on the head (Cabanac, 1993).

16.3.6 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).

In the cold, skin temperature has a more important role in thermoregulation than it does in the heat. The relative contribution from core and skin temperatures in eliciting shivering is between 4 and 5 to 1 when the skin is cold (Tikuisis and Giesbrecht, 1999; Stolwijk, 1971), compared to the 10 to 1 ratio seen for sweating. When the core becomes very cold, below 30 °C, the metabolic heat produced by shivering diminishes (Bristow and Giesbrecht, 1988); it is thought that the body does this in order to conserve energy for survival. Shivering onset requires simultaneous cold signals from both the skin and core. Shivering is not activated when a person is exercising in a cold environment with a cold skin temperature but high core temperature.

People with higher body fat shiver less at a given temperature due to the insulation provided by the fat. Shivering heat production is inversely proportional to the square root of body fat (Tikuisis and Giesbrecht, 1999). In addition, fatter people tend shiver less because they produce more metabolic heat by carrying the additional mass.

16.4 Heat exchange at the skin surface

16.4.1 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:

$$K = h_k\,(T_{skin} - T_{surface}) \quad (\mathrm{W/m^2}) \qquad [16.2]$$

where K is conductive heat transfer from the skin surface to a contacting surface.

In a transient state, the heat flux to and from a contacting environmental material will depend on the thermal inertia of that material, quantified as its volumetric heat capacity multiplied by its conductivity. The thermal inertia determines the amount of heat that the skin will gain or lose from contact with

Table 16.5 Values of thermal inertia of, and sensation of heat or cold given by, various substances

Material	Thermal Inertia ($J^2/m^4 K^2$ sec)	Threshold of pain (cold)	Temperature (°C) range of comfort	Threshold of pain (hot)
Steel	0.5×10^{-2}	14	29–32	45
Concrete	1×10^{-2}	4	27–34	54
Rubber	1.2×10^{-3}	–12	24–35	67
Oak	7.3×10^{-4}	–20	22–35	74
Pine	2.4×10^{-4}	–53	17–39	84
Cork	6.0×10^{-5}	–140	5–42	150

Houdas and Ring, 1982

that material over short-term periods. Houdas and Ring (1982) present a table of common materials, and the temperature ranges at which contact with them is comfortable, or produces hot or cold discomfort or pain (Table 16.5). For comparison, the thermal inertias of the body tissues themselves are: skin, $30–80 \times 10^{-4}$, fat $10–15 \times 10^{-4}$, muscle $30–60 \times 10^{-4}$, and bone $25–40 \times 10^{-4}$. Each of these is temperature dependent, reflecting blood flow and content.

16.4.2 Convection

Convective heat loss from the body surface is often expressed as a heat transfer coefficent and the difference between the mean temperature of the outer surface of the body and that of the surrounding air:

$$C = h_c\,(T_{\text{skin}} - T_a) \quad (\text{W/m}^2) \qquad [16.3]$$

where h_c = convective heat transfer coefficient ($\text{W/m}^2 \cdot \text{K}$)

Still-air convective heat transfer coefficients

If there is no air motion over the skin surface, a relatively thick layer of heated air will lie adjacent to the surface, and the temperature gradient across this layer is determined by the conductivity of air ($k = 0.024$ W/m K). However, in nature, the thermal gradient produces a buoyancy gradient in the air, which, depending on the air's viscosity and the orientation of the surface relative to gravity, will cause bulk motion that decreases the conductance of this boundary layer. The heat transfer through such a naturally convecting boundary layer is governed by the Nusselt, Prandtl, and Grashof numbers, which take into account the diffusion and bulk convection of heat.

Still-air convective heat exchange from the human body is dominated inevitably by a slow-moving buoyant plume of air that develops adjacent to the heated body surfaces, and rises along the body carrying heat, water vapor, and bioeffluents with it. The plume usually envelops the head, and affects the subject's breathing and olfactory senses, giving it an important effect on thermal sensation. The convective heat transfer to the plume depends on posture, clothing, and the local temperature of the air at various points in the plume. This has recently become the subject of computerized fluid dynamics (CFD) simulations (Murakami, 2004), and detailed laboratory visualizations using particle-tracing anemometry.

Since the free-convection process is complex, still-air convective dry heat loss coefficients have been obtained empirically. deDear *et al*. (1997) used a detailed thermal manikin whose individual body segments were electrically heated to maintain realistic skin temperatures, measuring the required wattage to obtain the heat transfer coefficient for each segment. Radiant losses were decoupled by varying the surface emissivity of the manikin. (This manikin's surface areas are shown in Table 16.1, Section 16.3.1.)

Table 16.6 gives some natural convective heat transfer coefficients (*hc*) for a nude thermal manikin standing and sitting in still air (velocity < 0.1 m/s), from deDear *et al*. (1997). These were obtained at a fixed skin-to-air temperature gradient of 12 K.

Using the same manikin, Oguru *et al*. (2002a) found the still-air coefficients to vary with the temperature difference between air and skin. He presents power functions for calculating them for each body part. For the overall body, seated, the coefficient is

$$hc = 0.78\ (T_{skin} - T_a)^{0.56} \tag{16.4}$$

and for the standing body,

$$hc = 1.21\ (T_{skin} - T_a)^{0.43} \tag{16.5}$$

Table 16.6 Natural convective heat transfer coefficients (hc) for a nude thermal manikin standing and sitting in still air (velocity < 0.1 m/s), Obtained at a fixed skin-to-air temperature gradient of 12K

Manikin segment	Seated natural convective coefficients (W/m^2 K)	Standing natural convective coefficients (W/m^2 K)
Foot (L and R)	4.2	5.1
Lower leg (L and R)	4.0	4.1
Thigh (L and R)	3.7	4.1
Pelvis region	2.8	3.4
Head	3.7	3.6
Hand (L and R)	4.5	4.1
Forearm (L and R)	3.8	3.7
Upper arm (L and R)	3.4	2.9
Chest	3.0	3.0
Back	2.6	2.9
Whole body	3.3	3.4

From deDear *et al.* (1997).

Moving-air convective heat transfer coefficients

Moving air increases heat transfer from the skin surface by reducing the thickness of the heated layer adjacent to the skin, and thereby increasing its conductance (W/m^2 K). The body's boundary layers are fundamentally characterized by the properties of air and the dimensions of the body's surfaces (Nusselt, Prandtl, and Reynolds numbers), with body segments represented with empirical values for cylinders. However, with the complexities of the human shape, such values are usually empirically determined on human-shaped manikins.

With the manikin in a wind tunnel, deDear (1997) and Oguro *et al.* (2002b) separately developed expressions for heat transfer coefficients as a function of air velocity. For the overall body, their values are close, as shown in Table 16.7.

They also obtained expressions for each body part, repeated for upwind, downwind, and sideways wind orientations. In general, the expressions are quite similar, regardless of direction, unless a given body part passes into the wind shadow of another body part (e.g. the arm and its adjacent torso, or the lower limbs while seated). The insensitivity to direction can be explained to some extent by the fact that most body segments are cylindrical and vertically oriented.

Air motion across the skin surface can also be caused by the motion of the body itself. For a walking or running person, the limbs experience higher and lower air velocities than the mean speed of the body as they swing back and forth. Chang *et al.* (1988) quantified values for various body parts using an articulated moving manikin mounted on a treadmill in a wind tunnel. They found that the convective coefficients for the outer limbs were lower than those for body parts closer to the trunk. This could be due to the non-linear relationship of convection to velocity; if for half of the swing cycle the arm or calf is almost stationary relative to the ground and the surrounding air, the reduction in convective loss will be great, and the doubled velocity during the other half of the cycle will not make up for it.

In the outdoors, it is common to express forced-convective heat transfer in terms of an ambient temperature at which equivalent heat transfer would occur; this is termed a 'wind-chill index' or 'wind-chill equivalent temperature' (WCET):

Table 16.7 Moving air convective heat transfer coefficients

Standing		Seated	
deDear	Oguro	deDear	Oguro
$hc = 10.4\ V^{0.56}$	$hc = 9.41\ V^{0.61}$	$hc = 10.1\ V^{0.61}$	$hc = 9.43\ V^{0.63}$

$$\mathrm{WCET} = T_{skin} - h_{actual}/h_{calm} \times (T_{skin} - T_a) \quad [16.6]$$

Shitzer (2005) has reviewed the historical formulations of the wind chill index. The index is usually developed for a simple geometrical shape such as a cylinder.

In cold weather, the skin develops bumps (gooseflesh) around hair follicles, and the hair itself 'stands on end' – pilo-erection. For fur-bearing animals, this serves to insulate the skin. For humans, the hair density on most of the skin has become thin, and both the hair and the muscular apparatus that erects it have evolved to be insignificant for thermoregulatory purposes. The hair on the head, however, is often thick enough to form a substantial insulative layer.

16.4.3 Long-wave radiant exchange

The radiation emitted from a surface is proportional to the fourth power of absolute temperature, but it is possible to approximate radiant exchange with a linear coefficient when the surfaces are within a limited range of temperatures.

$$R = h_r \times \varepsilon\,(T_{skin} - T_r) \quad (\mathrm{W/m^2}) \quad [16.7]$$

where h_r = radiative heat transfer coefficient (W/m^2 K), ε = emissivity, and T_r = the temperature of the surrounding surfaces. T_r is also represented by the 'mean radiant temperature' (MRT).

The linearized radiative heat transfer coefficient can be calculated by:

$$hr = 4\varepsilon\sigma \frac{A_r}{A_D}\left[273.2 + \frac{T_{skin} + T_r}{2}\right]^3 \quad [16.8]$$

where σ = Stefan–Boltzmann constant, 5.67×10^{-8} W/m^2 K^4, A_r = effective radiation area of the body A_D = total area of the body (Dubois area).

The ratio A/A_D is 0.70 for a sitting person and 0.73 for a standing person (Fanger, 1967). Emissivity is close to unity for the skin surface (typically 0.95). The coefficient h_r is nearly constant for typical indoor temperatures, and a value of 4.7 W/m^2 · K suffices for most calculations (Fanger, 1972).

Using the thermal manikin with its radiative and convective loss fractions separated, deDear *et al.* (1997) obtained h_r values for each segment of the unclothed body (Table 16.8). These apply to uniform radiant surroundings. Although the individual segment values differ substantially, the whole-body values are close to the Fanger value of 4.7 W/m^2 K.

When exposed to an asymmetric radiant environment, where the surfaces surrounding the body have different temperatures from each other, e.g. a cold or hot window in an otherwise neutral room, it is necessary to know the angle factors between the body and the surrounding surfaces to determine the radiative heat exchange with them. Angle factors require knowledge of

Table 16.8 Body segment radiative heat transfer coefficients (hr) for a nude thermal manikin standing and sitting in still air

Manikin segment	Seated radiative coefficients (W/m^2 K)	Standing radiative coefficients (W/m^2 K)
Foot (L and R)	4.2	3.9
Lower leg (L and R)	5.4	5.3
Thigh (L and R)	4.6	4.3
Pelvis region	4.8	4.2
Head	3.9	4.1
Hand (L and R)	3.9	4.1
Forearm (L and R)	5.2	4.9
Upper arm (L and R)	4.8	5.2
Chest	3.4	4.5
Back	4.6	4.4
Whole body	4.5	4.5

From deDear *et al.* (1997).

the projected area of the body from the direction of the surface with which the body is exchanging radiation. The whole body's projected areas were measured by Fanger (1967, 1972) for the full spherical surroundings of standing and seated persons. From these he calculated angle factors for a wide range of window sizes at varying distances from standing and seated occupants; these are universally used in standards and design (ASHRAE, 2005). Oguro *et al.* (2001b,c) extended this to measuring projected areas for each individual body part, again using the manikin in both standing and seated postures.

16.4.4 Short-wave (solar) gain to skin

The absorptivity of skin to solar radiation varies with skin color in the visible and the near-infrared spectra. For visible wavelengths (0.4–0.7 μm), white skin is about 0.5 absorptive, while black skin has been measured at 0.74 (Houdas and Ring, 1982). In the near infrared from 0.8 to 1.4 μm, white skin is 0.6 and black 0.7, while from 1.4 to 2 μm they are almost the same at 0.82, and above 2 μm, they both approach unity. For ultraviolet (<0.4 μm), both skin colors absorb at 0.85. Narita *et al.* (2001) tested subjective thermal sensations from equal radiation intensities at different wavelengths, and found that human skin is more sensitive to the visible (0.3–0.8 μm) and middle-infrared (1.7–2.3 μm) than to near-infrared (0.8–1.35 μm) wavelengths. This difference is attributed to the wavelengths' variable depth of penetration into the skin, relative to where the sensory nerves are located.

In the heat, light breathable clothing may be cooler for the wearer than exposing bare skin, if the clothing is pervious to evaporated sweat but shields the radiant heat from the sun. Offsetting the shading effect, clothing reduces convective exchange with the atmosphere, but this can be beneficial when T_{air} is greater than T_{skin}.

16.5 Moisture exchange at the skin surface

The heat lost to the environment by evaporation (E) is calculated using an evaporative heat exchange coefficient and the water vapor pressure difference between the skin and the ambient air. The equation is analogous to the convective heat transfer equation.

$$E = h_e\, w\, (P_{skin,\ saturated} - P_a) \quad (\mathrm{W/m^2}) \tag{16.9}$$

where h_e = evaporative heat transfer coefficient (W/m^2 kPa), w = skin wettedness (dimensionless), $P_{skin,saturated}$ = water vapor pressure at the skin surface, assumed to be the pressure of saturated air at the skin temperature (kPa), and P_a = water vapor pressure of the ambient air (kPa).

The evaporative heat transfer coefficient h_e for the outer air layer of a nude person can be estimated from the convective heat transfer coefficient h_c using the Lewis ratio, which describes the relationship between convective heat transfer and mass transfer coefficients for a surface:

$$LR = h_e/h_c \tag{16.10}$$

The Lewis ratio equals approximately 16.5 K/kPa for typical indoor conditions.

Evaporative heat loss from the skin depends on the amount of moisture on the skin and the difference between the water vapor pressure at the skin and in the ambient environment.

Skin wettedness is the ratio of the actual evaporative heat loss to the maximum possible evaporative heat loss, *Emax*, under the same environmental conditions and a completely wet skin (w = 1). Evaporative heat loss from the skin is a combination of the evaporation of sweat secreted because of thermoregulatory control mechanisms and the natural diffusion of water through the skin. With no regulatory sweating, skin wettedness caused by diffusion is approximately 0.06 for normal conditions. For large values of *Emax* or long exposures to low humidities, the value may drop to as little as 0.02, because dehydration of the outer skin layers alters its diffusive characteristics.

Skin wettedness is strongly correlated with warm discomfort. For clothed subjects, $w > 0.2$ is perceived as uncomfortable. Skin wettedness can theoretically approach 1.0 while the body still maintains thermoregulatory control, but in practice it is difficult to exceed 0.8 (Berglund and Gonzalez, 1977).

16.5.1 Control of evaporation from damaged skin

Wounds (burns and scrapes) that remove the stratum corneum expose a fully wetted saturated surface. Evaporation from a wounded surface may cause heat loss 3 times that of dry heat loss and equivalent to vigorous sweating (Maglinger *et al.*, 2005). This creates a serious problem in cool operating theaters because anesthetic-induced inhibition of normal thermoregulation is likely to cause patient hypothermia. Surgical drapes and bandages are used to reduce moisture and heat loss.

Ordinary surgical drapes reduce cutaneous dry heat loss by 30% during operations and prior skin preparation (Sessler *et al.*, 1991). Making the surgical drapes impervious to moisture may reduce evaporative heat loss, as well as preventing contamination of the surgical sites from fluid passing through the drape.

Bandages were traditionally cotton and polyester but have expanded into numerous types of porous and nonporous fabrics, foams, and films (van Rijswijk and Beitz, 1998) including bioactive dressings that accelerate healing and grow with the skin (Bhowmick *et al.*, 2003). They provide a moisturized microenvironment, reduce fluid loss, wick away bacteria and exudates, and prevent bacteria from penetrating. Bandages help to fulfil the functions of the natural skin.

16.6 Typical skin temperatures

The core temperature is maintained within a small range, about 36–38 °C (Fig. 16.1). The skin temperature may change significantly in order to keep the core temperature in that range, and its temperature will be sensed by the thermoreceptors in the skin (Fig. 16.6). However, the skin temperature is not uniform across the different segments of the body, due to a variety of physiological factors. The inter-segment temperature variation has entirely different patterns in the cold versus in the heat, when the body is either attempting to conserve or reject metabolic heat. Skin temperature distributions are described below for three conditions: neutral, cold, and warm.

Skin temperature distribution under conditions perceived by the subjects as neutral are provided in Table 16.9. The UC Berkeley data were taken with the subject wearing a thin leotard over the temperature sensor (Zhang, 2003). The data provided by Olesen and Fanger (1973) were taken with subjects wearing office clothing. It is unclear why the Berkeley data are consistently about 1K higher than the Olesen and Fanger data, but the distribution patterns are consistent.

In cold environments, skin temperature varies widely across the body as a whole, and even within many individual body parts, due to the effects of vasoconstriction. In the cold, the fingers and nose are the coldest, and finger

Table 16.9 Local skin temperatures (°C) in neutral stable condition

Segment	Skin temperature (°C) – UC Berkeley	Skin temperature (°C) – Olesen and Fanger
Forehead	35.8	34.2
Cheek	35.2	
Front neck	35.8	
Back neck	35.4	
Chest	35.1	34.5
Back	35.3	34.4
Abdomen	35.3	34.9
Upper arm	34.2	33.5
Lower arm	34.6	32.7
Hand	34.4	33.5
Left finger	35.3	
Thigh	34.3	33.7
Shin	32.9	32.6
Calf	32.7	32.2
Foot	33.3	32.2
Average	34.45	33.38

Table 16.10 Local skin temperatures in a cold stable condition (°C)

Segment	Skin temperature (°C)
Forehead	30.7
Cheek	27.7
Front neck	33.5
Back neck	34.5
Chest	30.9
Back	32.4
Abdomen	28.7
Upper arm	24.7
Lower arm	27.3
Hand	23.1
Left finger	21.1
Thigh	27.0
Shin	26.5
Calf	24.3
Foot	21.4
Average	26.8

temperature is 9 K colder than the forehead temperature. The neck temperature is the warmest and can represent a significant source of heat loss (Table 16.10).

In warm environments, skin temperatures are more uniform than in cold. The skin temperatures are evenly distributed, with only a small variation of 2.7 K (Table 16.11). Unlike the cold, the fingers and feet are dilated, and

Table 16.11 Local skin temperatures in a warm stable condition

Segment	Skin temperature (°C)
Forehead	36.5
Cheek	36.3
Front neck	36.8
Back neck	36.1
Chest	36.1
Back	36.3
Abdomen	36.2
Upper arm	36.4
Lower arm	36.1
Hand	36
Left finger	36.7
Thigh	35.6
Shin	34.4
Calf	34.1
Foot	36.4
Average	35.8

have some of the warmest surface temperatures on the body. The upper torso and extremities are very uniform. The lower extremities (thigh, lower leg) are colder than the areas above the pelvis, because in sitting they have not moved as frequently as the hands and arms. A following section describes how movement increases finger and hand skin temperatures.

16.6.1 Finger skin temperature in extreme cold environments

Finger dexterity is decreased when the finger skin temperature is below 15 °C. If finger tissue temperature reaches freezing, frostbite occurs, which can cause permanent damage to the tissue and permanently impair circulation. The body has a defense mechanism in cold-induced vasodilatation, which periodically delivers warm blood to the freezing tissue. The vasodilatation occurs because the smooth muscle in the blood vessel walls becomes fatigued or paralyzed and cannot continue the vasoconstriction. A similar effect can be obtained by heating the chest or torso, which increases hand and finger skin temperatures by triggering increased circulation of blood to the extremities (Bader and Macht, 1948; Brajkovic *et al.*, 1998, 2003).

16.6.2 Neck

The neck has the highest skin temperature of any body part when a person is cold. In IR images taken in a cold environment, the warm neck is very noticeable, like a bright collar. This justifies turning up jacket collars or putting on a scarf in cold weather. (Zipping up the collar of a jacket also restricts the pumping effect of the air through the opening of the collar, which removes heat from the larger torso area).

16.6.3 Hand

The hand is probably the most active body part in responding to the body's thermoregulation requirements. In warm conditions, the hand is fully vasodilated and the fingertips are the warmest areas of the hand. This pattern is reversed when cooling. Constriction of the hand blood vessels causes the skin temperature of the hand to vary on the order of 8 °C. When the hand is cold, it ceases to transfer much body heat to the environment.

The hand is very sensitive to the body's overall thermal state. An IR image taken a few minutes after the subject moved from a warm environment (30 °C) to a slightly cool (22.6 °C) environment, showed that, although the rest of the upper body temperature has not changed much yet, the blood vessels of the hand were already well constricted. A 3 K difference in finger skin temperature has been observed in slightly cool environments, caused by the difference in muscular exertion between typing *vs* holding the computer mouse (Table 16.12 – Huizenga *et al.*, 2004).

16.6.4 Skin temperature during sleep

Skin temperature increases, and core temperature decreases, prior to and during sleep onset (Van Someren, 2004; van den Heuvel, *et al.*, 1998; Gilbert *et al.*, 2000). To preserve heat, people normally would cover themselves with blankets to create a microclimate of 34 °C (Muzet *et al.*, 1984), which is much warmer than the normal environment for comfort when awake (28–30 °C for a nude person). Measures that increase skin temperature may also help people fall asleep (Van Someren, 2004), as long as the high skin temperature does not evoke warm discomfort. Warming the extremities (feet) is especially effective (Krauchi *et al.*, 1999).

Table 16.12 Effect of using a computer mouse on fourth finger temperature (°C) in cold, neutral, and warm environments. Skin temperatures were measured at the end of a two-hour test

	T_{air}: 15.6	T_{air}: 19	Neutral	T_{air}: 30
Left	21.1	21.1	35.4	36.4
Right (using mouse)	17.8	19.3	34.7	36.2

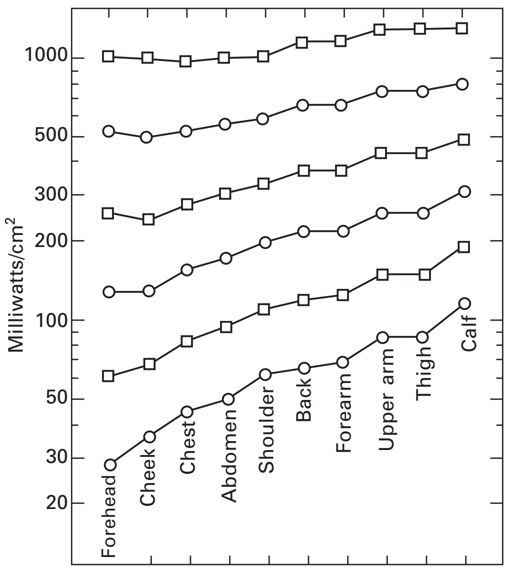
16.7 Sensation and comfort

16.7.1 The distribution of thermal sensitivity

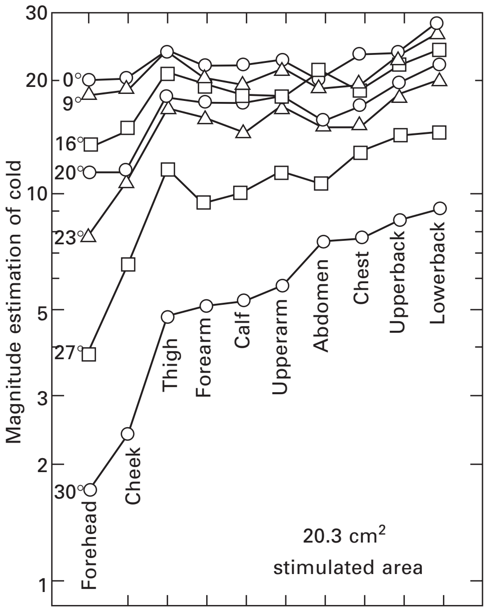
Much research exists on how thermal sensitivity is distributed across the body, and across specific areas of the body. We will focus here on sensitivity differences found across the body as a whole.

Regional sensitivity to warmth (Stevens *et al*. 1974) and cold (Stevens 1979) has been examined. For warmth, thermal stimulation was provided by heat lamps, which eliminated any touch stimulation. The skin surfaces measured are shown in Fig. 16.10. The subjects judged the degree of warmth sensation using the method of magnitude estimation, i.e. the assignment of numbers to match sensation. The forehead and cheek are the most sensitive, followed by: chest, abdomen, back, thigh, and calf. At the higher levels of radiation, the differences were less pronounced.

In the cold sensitivity test, an aluminum contact stimulator was used on the same body surface locations (Fig. 15.11). For cold, the trunk region (including the thighs is the most sensitive, followed by the limbs; the forehead and cheek are the least sensitive.



16.10 Equal-warmth profile. Each contour shows the irradiance level needed to produce a given constant level of warmth (From Stevens *et al*., 1974 with permission from Elsevier).

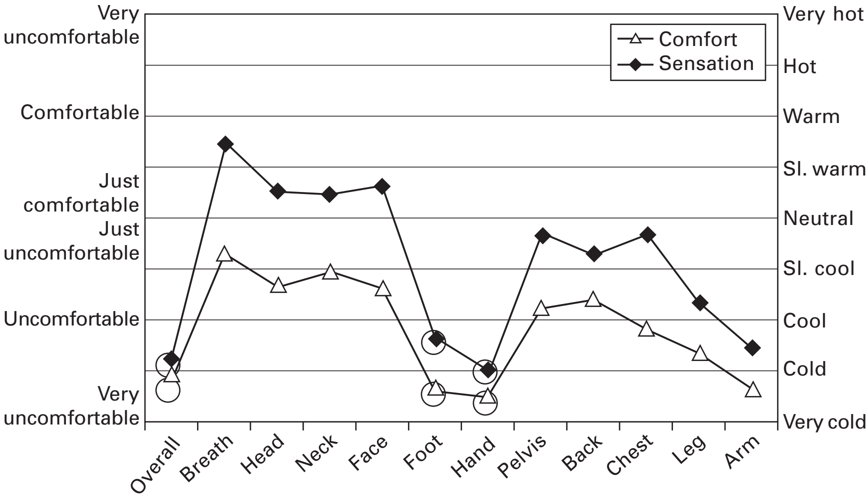


16.11 Magnitude estimation of cold sensation, arranged in order from the least sensitive (forehead) to the most sensitive (lower back), for different levels of cold stimulation (From Stevens, 1979, with permission from Elsevier).

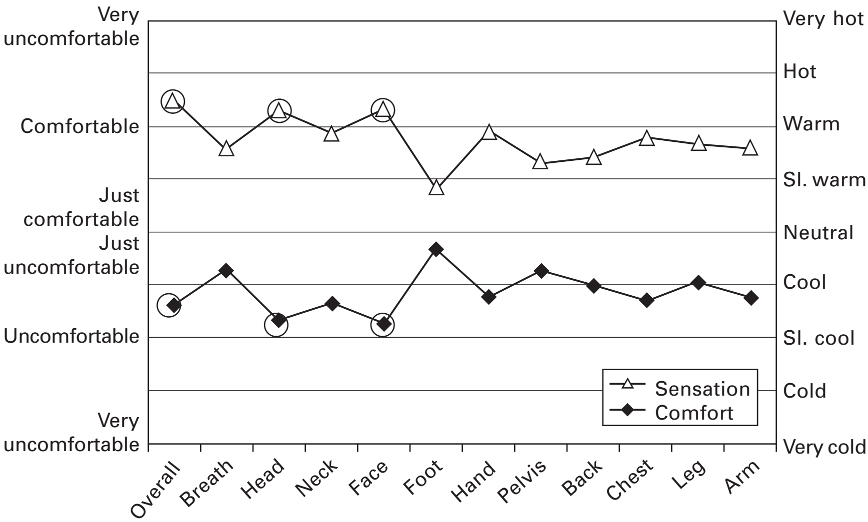
16.7.2 Thermal sensation and comfort distributions under uniform environments

Sensation and comfort for local body parts vary greatly in subjects exposed to uniform environments (Arens *et al.*, 2006a,b; Zhang, 2003). In cool environments, the sensation difference from the least cold sensation (breathing zone, 'slightly cool') to the coldest (hand, 'very cold') is more than 2.5 units on the sensation scale. The hands and feet feel colder than other body parts (Fig. 16.12), and their skin temperatures are also the lowest. A local skin temperature distribution in a cold room (15.6 °C, Table 16.10) shows hand and feet skin temperatures to be about 9 °C lower than the forehead skin temperature. The head, insensitive to cold but sensitive to warm, feels warmer than the rest of the body in cold environments. The subjects' overall sensation follows that of the coldest (hands and feet) in cool environments.

The comfort for all body parts varies considerably – almost four comfort scale units (from 'very uncomfortable' to 'comfortable'. Although the whole-body sensation is cold and the local sensations for the head region (head, face, breathing zone, neck) are also cool, the local comfort for all the head parts is on the comfortable side. The comfort for the remaining body parts is all uncomfortable. The overall comfort follows the worst local comfortable



16.12 Local and overall thermal sensation and comfort in a uniform/cold environment.



16.13 Local and overall thermal sensation and comfort in a uniform/warm environment.

votes closely (marked by circles), the head region comfort exerting little apparent influence.

In the warm environment, there is still a considerable variation in sensation between body parts. The sensation distribution (Fig. 16.13) shows the variation to be about 1.5 scale units from the head or face (sensation above 'warm' at

2.3) to the feet (sensation 'slightly warm' at 0.8). The variation in skin temperature is much smaller (2.7 °C, Table 16.11) than in the cold environment, and the sensation distribution does not follow the skin temperature as closely. Unlike in the cold environment, where the overall sensation is driven by the vasoconstricted extremities, in the warm environment the overall sensation follows the head region sensation (the warmest local sensation) closely.

Unlike the distribution of local comfort seen in the cold environment, all the local comfort levels are uncomfortable, with the head region perceived as the most uncomfortable. Again, the overall discomfort value is close to the level of the head region discomfort, and could be predicted by the worst one or two local comfort values.

The sensation of the head – insensitive to cold but sensitive to warm – matches the thermal sensitivity presented by Stevens (1974, 1979) described earlier. From the above two figures, we see that head is not only relatively insensitive to cold, but comfortable with the cool sensation.

16.7.3 Sensation and comfort related to skin temperature

Although the contribution of core temperature to the body's thermoregulation is much stronger than the contribution of skin temperature (e.g. about 10:1 for sweating, 4:1 for shivering), for determining subjective thermal sensation, skin and core temperatures have equal importance (Frank *et al.*, 1999).

Within a small range of skin temperatures around neutral, thermal sensation does not change. In this range the setpoint for sensation adapts to the current skin temperature, and people are comfortable (McIntyre, 1980). The range is considerably greater for the extremities than the torso (Zhang, 2003). This is shown in Table 16.13. The set point adaptation occurs over periods of time,

Table 16.13 Ranges of comfortable skin temperatures by body part

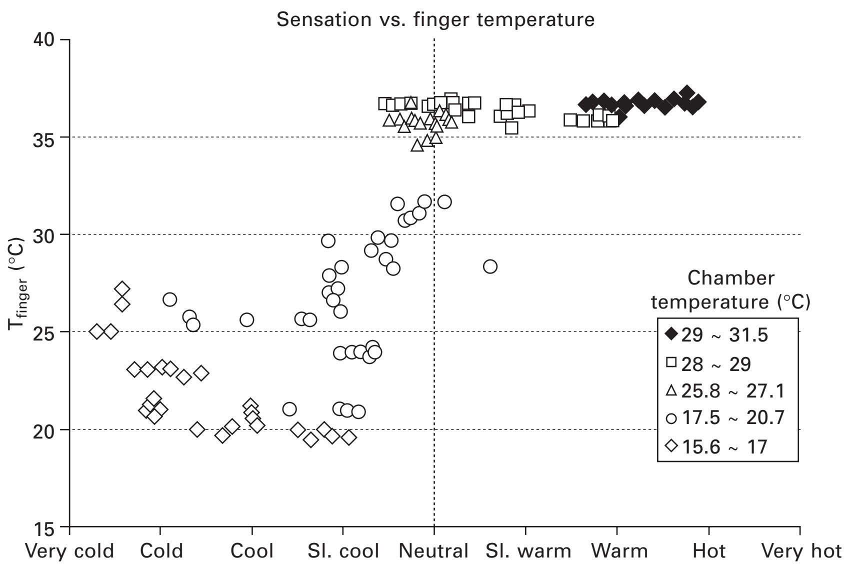
Body part	T_{low}	T_{high}
Head	33.8	35.8
Face	32	36.2
Breath	31.7	35.2
Front neck	36.0	36.6
Chest	33.8	35.4
Back	33.8	35.8
Pelvis	32.6	34.8
Upper arm	31	34.6
Lower arm	31	36.5
Hand	30	36
Thigh	31.6	34.8
Lower leg	31.8	35.1
Foot	30.8	35

varying from seconds for small surface areas, to minutes when the areas are larger.

16.7.4 Thermal sensation related to finger skin temperature

Figure 16.14 presents subjects' overall thermal sensation votes and corresponding finger temperatures obtained during the final 10 minutes of hour-long stable condition tests, in chamber air temperatures from 15.6–31.5 °C (Wang *et al.*, 2006). Each subject registered 6 votes. When subjects felt warm or hot (their overall sensation between 0.5 and 2.8), their finger temperatures were closely bunched around 37 °C, close to the core temperature. On the cool to cold side (overall sensation less than –0.5), finger temperature ranged widely between 20–30 °C.

Whenever finger temperature was above 30 °C, the overall sensation was above –0.5 (the lower boundary of the neutral sensation zone), and there was therefore no cool discomfort ($p < 0.001$). When finger temperature was below 30 °C, whole-body sensation was (with the exception of a few data points) always below –0.5 ($p < 0.001$), and therefore, cool discomfort was a possibility. 30°C is a clear threshold, separating warm from cool. All the actual discomfort votes occurred below 28 °C (overall thermal sensation < –1.5).



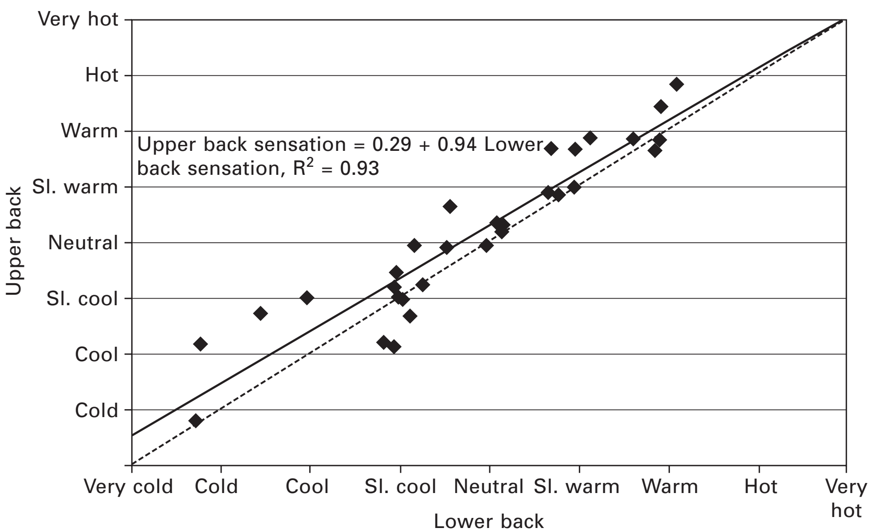
16.14 Whole-body sensation *vs* finger skin temperature.

16.7.5 Upper and lower back

Figure 16.15 compares upper back and lower back thermal sensations. The thermal sensation for the upper back is warmer than for the lower back (Arens *et al*., 2006a). When the lower back sensation is neutral (scale value 0), the upper back feels warm (scale value 0.3). When the upper back is neutral, the lower back is already cool. This is also consistent with the thermal sensitivities which show the lower back to be more sensitive to cold than the upper back (Section 16.7.1). These sensation results apply also to comfort (not shown here). In warm environments, the upper back feels warmer (and more uncomfortable) than the lower back. In cool environments, the lower back feels colder (and more uncomfortable) than the upper back. A heated chair (Knudsen and Melikov, 2005) can be an effective solution to this thermal sensitivity.

16.7.6 Neck, face, ankles

In cold, the neck always has a high skin temperature. Consequently, people feel particularly susceptible to drafts impinging on the back of the neck. Yet air movement from the side of the head is generally regarded as pleasant and effective at cooling in warm environments. This directional asymmetry suggests that lightweight clothing designed to shield the back of the neck (with a relatively high collar) could be very adaptable for thermoregulation, especially in environments such as offices, where people tend to be oriented in a fixed direction for long periods of time.



16.15 Comparison between upper and lower back thermal sensations.

16.7.7 Moisture effects on comfort

Wet skin discomfort

Humans have no known sensors that directly detect humidity, but they are sensitive to skin moisture caused by perspiration, and skin moisture is known to correlate with warm discomfort and unpleasantness (Berglund and Cunningham, 1986). It is rare for a sedentary or slightly active person to be comfortable with a skin wettedness greater than 25%. The proposed mechanisms for discomfort are related to the swelling of the epidermis as it absorbs moisture (Kerslake, 1972). Berglund (1995) suggested that the skin's swelling may stimulate the skin's tactile mechanoreceptors in some way and be perceived as uncomfortable.

In addition, mechanoreceptors are clearly stimulated by the friction of clothing moving across the skin surface. With moisture absorption, the stratum corneum outer layer softens, allowing clothing fibers to dig in and increase friction. The additional friction is perceived as fabric coarseness and cling (Gwosdow *et al.*, 1986). Moisture-induced cling effect also occurs with architectural and furniture surfaces, particularly smooth, non-hygroscopic materials (ASHRAE, 2005).

Fabrics with different moisture absorbance properties are potentially perceived differently, but there is little experimental evidence for this at present. Toftum *et al.* (1998a) studied knitted and woven cotton and polyester clothes under controlled levels of skin relative humidity ranging from 10 to 70%, and found that fabric type had no effect on comfort, or on perceived humidity of skin or fabric. He found the acceptance of skin humidity decreases as the skin's relative humidity increases, and produced a predictive model of this. It should be noted that, for normal environments where air temperature is less than skin temperature, the effect of the *air's* relative humidity is much less than that of the skin's relative humidity. For cool environments, very high air relative humidity produces almost no perceived skin comfort effect; even at the warm limit of the comfort zone, 70% air relative humidity causes less than 15% of subjects to perceive discomfort due to skin humidity.

Dry eye syndrome

Dry eye discomfort is caused by thinning or sometimes rupturing of the precorneal tear film (PTF) which defends the ocular surface from exposure to the environment. Dry eye can be caused by high temperature, low relative humidity, and indoor pollutants affecting the PTF (Wolkoff *et al.*, 2003, 2005). The body's thermal plume, clinging to the face, acts to protect the PTF from excessive heat and moisture losses, but air movement across the face can disrupt the plume and hasten PTF evaporation (Murakami, 2004). Dry eye stimulates eye blinking in order to restore the moisture on the PTF;

indeed eye-blinking frequency is used as a measure to investigate dry eye discomfort (Nojgaard *et al*. 2005).

Respiratory tract comfort

Insufficient evaporative and convective cooling of the mucous membranes in the upper respiratory tract may cause local warm discomfort and a sense of stuffiness and staleness when temperature and humidity are high. This effect is many times more noticeable immediately after a step-change in humidity than after a period of exposure to the humidity. In determining the sensation of staleness, 1K drybulb temperature is equivalent to 1K dewpoint temperature after 15 sec exposure, whereas 1K drybulb is equivalent to 6K dewpoint after 60 minutes of exposure (Berglund and Cain, 1989; Toftum, 1998b).

16.8 Modeling human thermal regulation and comfort

There are numerous models of human thermoregulation and of the resulting perceived thermal sensation and comfort. They can be divided into whether they are static or dynamic, whole-body or multisegment, physical or empirical.

The most commonly used comfort model is the Fanger Comfort Equation, or 'predicted mean vote' (PMV) model, which now forms the basis of the ASHRAE and ISO indoor environmental comfort standards (Fanger, 1972). The model predicts the mean thermal sensation (PMV) and the 'predicted percentage dissatisfied' (PPD) of a large population. It bases the PMV and PPD on a physical prediction of the heat flow from the body to the surrounding environment, relative to the heat flow required for comfort (this is a function of metabolic rate). The prediction is applicable only in steady-state conditions, and the whole body and its clothing are treated as a uniform object. The thermal sensation and discomfort outcomes are empirically based on data from chamber studies of a large number of subjects.

A model capable of dynamically simulating transient conditions was developed by Gagge *et al*. (1971, 1986). This 'two-node model' treats the body as a core and a skin shell, with the whole body surface treated uniformly. Skin and core temperatures are simulated by a physiological model of the heat transfers between core, skin and the environment, using dynamic thermoregulatory control functions for sweating, vasodilatation and constriction, and shivering. The skin and core temperatures are then the basis for a prediction of thermal sensation, which in turn is combined with skin wettedness to predict comfort.

The *ASHRAE Handbook of Fundamentals* provides the underlying equations for the PMV and the two-node models, and the models are compared in detail in Doherty and Arens (1988). Both models are incorporated in user-friendly software available from ASHRAE.

Multi-segment models have been developed to account for the differences in clothing, heat transfer, and thermal sensitivity that occur on a real body, especially when the body is exposed to a non-uniform environment. Like the two-node model, they are dynamic and are based on simulations of the physiology in the body. Most multi-segment models originated with Stolwijk and Wissler in the early 1970s (Wissler, 1964; Stolwijk, 1971). The body is divided into segments (e.g. head, trunk, leg, foot, arm, hand), and each segments into four layers (core, muscle, fat, skin). The models vary in their detail and treatment of the thermophysiology, but most of them (Smith, 1991; Wang, 1992; Tanabe, 2002; Fiala, 1998) calculate the thermal sensation outcome on a whole-body basis.

The University of California at Berkeley developed a multiple-segment physiology and comfort model (Huizenga *et al.*, 2001; Zhang *et al.*, 2003) that calculates thermal sensation and comfort for each body segment, based on segment-specific human subject tests. It predicts whole-body sensation and comfort by integrating the sensations from all the body parts.

In addition to the physical models above, deDear and Brager (2002) developed an entirely empirical model of human adaptation to the environment. It is based on extensive studies of thermal sensation and comfort carried out in office buildings around the world, in which the range of acceptable environments varied widely, especially for buildings without air conditioning. The concept of the adaptive model is that when people are subjected to a given thermal environment over time, they adapt physiologically, psychologically, and behaviorally. The comfort ranges for these people are different from people who have not adapted to the environment. This model is now incorporated in the ASHRAE (2004) comfort standard, applicable for buildings with openable windows.

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