16
The skin's role in human thermoregulation and comfort

E. ARENS and H. ZHANG, University of California, Berkeley, USA

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.

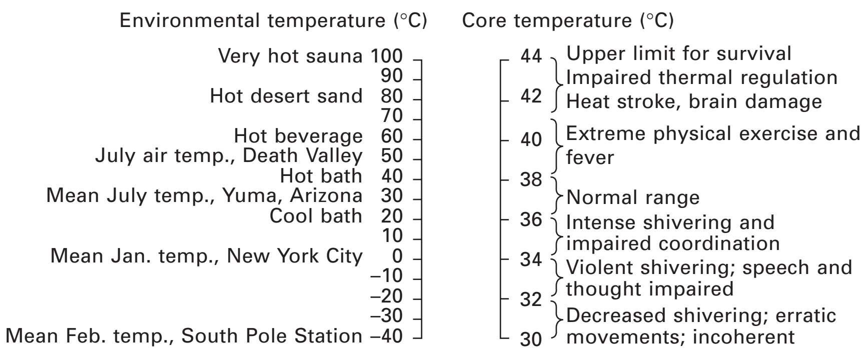
This chapter gives a brief description of the body's skin structure and thermoregulatory system, followed by a more detailed description of how heat and moisture are transferred at the skin's outer boundary, and finally, the comfort implications of skin temperature and humidity. Since skin characteristics 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.

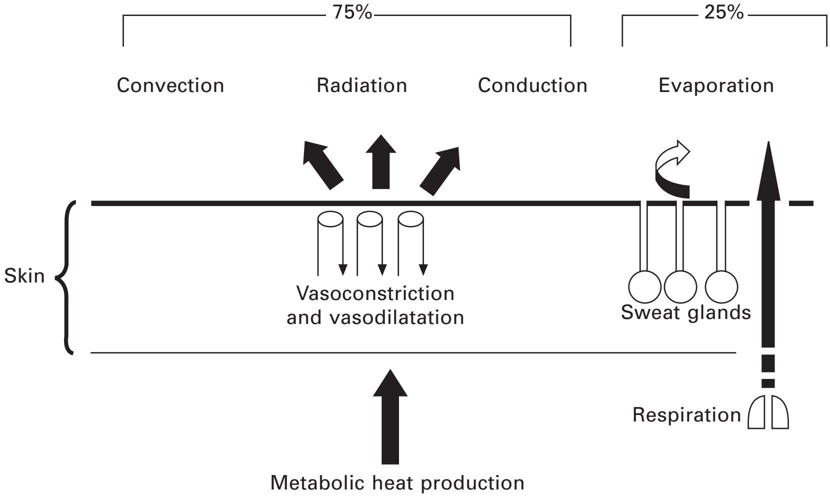
To normalize among people of different sizes, metabolism is typically expressed in per unit skin surface area. A specialized unit, the 'met', has been defined in terms of multiples of basal metabolism: 1 met is 58.15 W/m^2. A sleeping person has a rate of 0.7 met, and reclining awake is 0.8 met. Office 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):

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

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

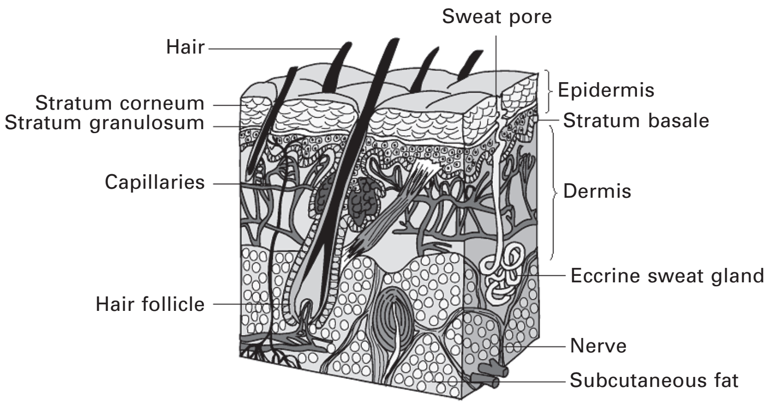
The skin provides a first barrier between the organism and its environment. It keeps the uncontrolled loss or gain of water through the skin at a low constant level. In addition to that, it contains complex vascular systems and sweat glands that allow it to change its conductance in response to thermoregulatory 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).

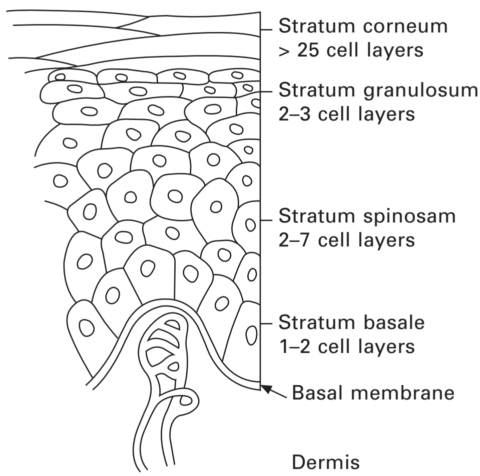
The epidermis is thin, mostly about 0.075–0.15 mm (except for the soles and palms, which are thicker). The outermost layer of the epidermis is the

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).

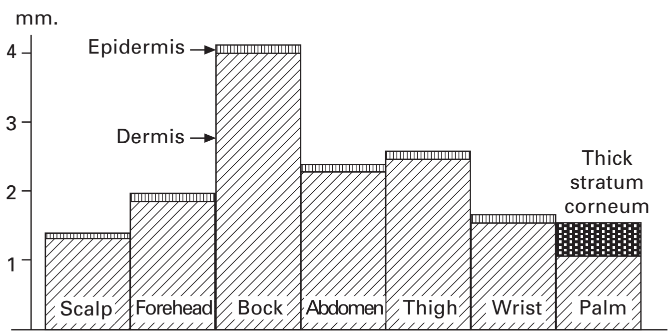
stratum corneum (Fig. 16.4), an assemblage of overlapping plate-like cells (corneocytes), interleaved with hydrophobic layers of lipids. The stratum corneum is 0.01 to 0.1 mm thick, and serves as the skin's primary barrier to water diffusion. Because the corneocytes are impervious to water transmission, 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,



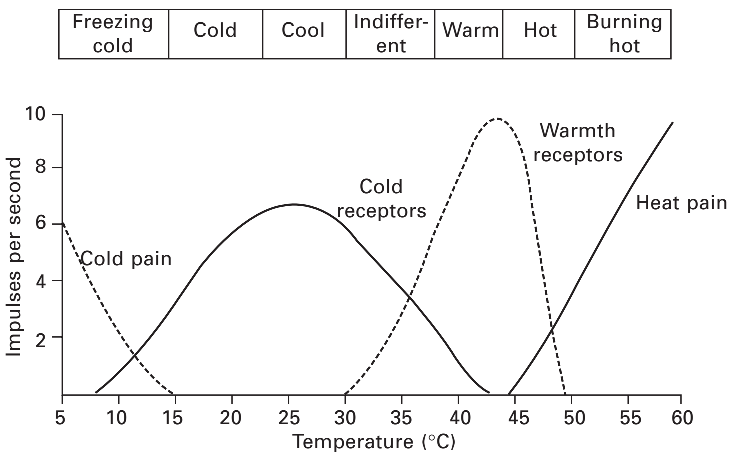
16.5 Regional variations in thickness of skin (From Rushmer *et al.*, 1966, with permission from the American Association for Advancement of Science, Washington, D.C.).

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

Capillaries

Arteriole