Chapter 29

Body temperature and clinical thermometry

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Abstract
In this chapter, the nuance of body temperature is explored in the context of contemporary clinical medicine and technology. It takes the reader through the concept of body and shell as a route to explain the variety of temperature measurements that are observed in health and disease and the interdependence between skin and core temperature in maintaining thermal stability and thermal comfort perception.

Methods for the measurement of temperature using different thermometer devices are discussed from the perspective of fundamental clinical assessment and vital signs, temperature monitoring and measurement for life-critical decision making, thermometry in mass screening, and to the future with advances in thermometry and thermography in new applications for diagnosis.

INTRODUCTION
Measurement of the temperature of the human body is one of the most widely performed clinical assessments undertaken in contemporary healthcare. As there are so many different clinical settings in which temperature taking is performed, the purpose of obtaining a measurement may vary from a routine health screen (occupational screening, primary care) to information for life-critical clinical decision making in the setting of intensive care and anesthesia. Here, high (or low) temperature values have been associated with a worsened patient outcome, morbidity and mortality, especially after severe traumatic brain injury (Childs et al., 2006; Sacho et al., 2010; Madden and DeVon, 2105).

In taking a temperature, it is probably fair to say that measurements are taken by a variety of users on a spectrum of knowledge and expertise: from healthcare novice to highly trained clinician. It follows that the understanding and interpretation of temperature values are likely to follow a similar trajectory. Put simply, whether the reading is normal or not on one level (and sufficient in many circumstances of screening for infection) to situations where patients are critically ill. Here, knowledge of temperature fluctuations, on a minute-by-minute basis, will have a significant impact for healthcare, influencing timely and appropriate therapeutic interventions intended for best possible survival (Drewry et al., 2013; Madden and DeVon, 2105).

In the main, taking temperatures, whether in the community or hospital, is a nurse-led activity; the objective is to detect a deviation from the “normal” range, a classic sign of disease. The exception to this is in clinical research, where advanced systems of thermometry such as proton magnetic resonance spectroscopy (¹H MRS) (Cady et al., 1995; Childs et al., 2007) and imaging (Thrippleton et al., 2014; Rango et al., 2015) are used for internal thermometry of core organs.

In many ways, the term “body” temperature is misleading, for the body is comprised of a mixture of tissues and structures, the temperatures of which can vary, albeit slightly, between organs. It is now almost 60 years since Wilhelm Graf (1959) reported temperature differences of internal organs. Key here were the findings that human liver temperature (36.7°C) was 0.21°C lower than rectal temperature (36.9°C), the difference significant ($p < 0.001$) at 0.2°C. In a separate series of investigations, simultaneous measurements in stomach and liver revealed that, as for rectum, liver temperature was consistent with previous

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findings (36.7°C), 0.14°C lower than gastric temperature. The results show two important observations: that rectal temperature is higher than gastric temperature and gastric temperature is higher than liver temperature. From a thermoregulatory perspective these differences, in health, show subtle variations in the temperature of internal organs, even though the differences are small from a clinical measurement point of view.

The situation can, however, change in disease. In neurologic damage (traumatic brain injury, subarachnoid hemorrhage, stroke), for example, brain tissue temperature can dissociate from core (rectal, jugular bulb) temperature and has variously been reported to be higher, the same, or lower than core temperature.

In a systematic review, Childs and Kueh (2013) showed that dissociation between brain and core temperature could be both positive (brain higher than body temperature) and negative (brain lower than body temperature). The polarity (direction) of the differences between brain and body temperature appears to be influenced by factors such as disease severity and therapeutic temperature control by body cooling. It seems that there is no consensus for the direction of the relationship between brain temperature and other measures of body core temperature in conditions where measurement of brain temperature can be justified, for example, after cardiac arrest (Coppler et al., 2016) and severe traumatic brain injury (Childs and Shen, 2015).

When considering the temperature variations that exist between internal structures as well as the differences in temperature at the skin surface (Maniar et al., 2015), it becomes clear that when we talk of body temperature, there is a need to be precise about the site upon (or in) the body that the clinician has selected for measurement.

Although the majority of temperature-measuring devices currently available in modern clinical practice have a relatively comparable performance with accuracy typically within 0.2°C (Childs and Machin, 2009), the precision and care taken in taking a temperature together with the performance of “downstream” bedside monitoring systems could ultimately have a greater impact on the measured temperature reading than the accuracy of the thermometer per se. The objective of this chapter therefore is to understand the nuance that constitutes human body temperature and the methods in current use by which it is measured – clinical thermometry.

**WHAT DO WE MEAN BY BODY TEMPERATURE?**

Over the course of the day, heat is produced within the body and heat is lost to the environment. Under physiologic conditions, heat production is balanced against heat loss and in homeotherms (warm-blooded creatures) internal temperature remains relatively constant. This physiologic stability of body temperature is consistent across mammals and birds and is achieved by a relatively “tight” thermoregulatory control. However, the “regulated” range is not consistent across the animal kingdom. In camels, for example, the range of body temperature is reported to be 4.5°C (i.e., 35.5–40°C), whereas in humans the range is small: 1°C (i.e., 36.5–37.5°C) (Stainer et al., 1984).

Within the regulated range for humans, temperature fluctuates over the course of a day but even in febrile illness it rarely rises above 41.1°C (106°F) (DuBois, 1949). This is thought to be due to a biologic “ceiling” (Mackowiak and Boulant, 1996) of regulated control.

A typical example of a regulated rise in temperature occurs during fever. Here, the balance point for thermoregulation (typically 37°C in health) is readjusted upwards from the healthy (nonfebrile) state to a readjusted balance point (for example, 38.5°C). Heat is produced and conserved to achieve the new “balance point” but the key point to remember is that temperature regulation continues, albeit at the higher level. It is worth noting that the administration of antipyretics such as acetaminophen (Tylenol) can lead to large fluctuations in temperature, mimicking a “swinging” pyrexia, a classic sign of the febrile disease malaria (Oyakhirome et al., 2010).

However, not all increases in body temperature are regulated. During hard work, extreme effort and high environmental temperatures, the heat energy produced during exertion may not be adequately matched by loss of body heat. Heat overload can occur. Adults will usually adjust their clothing (behavioral thermoregulation) to allow for loss of body heat and with sweating, a principal mechanism for heat loss in the warm body, temperature can be controlled via efferent thermoregulatory mechanisms, so preventing heat overload and hyperthermia. In other circumstances heat retention and hyperthermia can occur incidentally, for example, in the “overwrapping” of infants (Bacon et al., 1979; Wailoo et al., 1989) in hot ambient conditions. Here, body insulation due to excessive clothing and blankets leads to heat retention exacerbated by a reduced body surface area for heat dissipation. With the balance point unchanged and in the presence of increased heat storage, the rise in body temperature which follows is a consequence of hyperthermia rather than fever.

In hard exercise, body temperature may also increase. In elite athletes, running and cycling, for example, the intensity of exercise can increase body temperature in excess of 38°C (Gant et al., 2004).
has been debate as to the mechanism of thermoregulatory control during exercise, whether regulated or unregulated, which can be traced to the work of Marius Nielsen in 1938 (Johanssen, 1997). Nielsen’s experiments showed that, during brief bouts of intense exercise, muscle temperature reached 39°C within just a few minutes. With increased convection via the circulation, heat is dissipated to the rest of the body, resulting in fluctuations in core temperature. In more prolonged exercise, however (in excess of 40 minutes), heat is stored in the body with a concomitant increase in core temperature. Accompanying this rise in temperature is activation of heat dissipation mechanisms via the efferent limb of the thermoregulatory system. After approximately 20–30 minutes a balance between heat produced and heat lost is achieved and core temperature is maintained at a higher level, described as the “prescriptive zone” (Lind, 1963).

Saltin and Hermansen (1966) on re-examining the relationship between deep body temperature and exercise intensity (during submaximal work) observed that the increase in body temperature was not due to failure of thermoregulation (i.e., hyperthermia) but to a change in the “balance point.”

There is little information exploring the effect of hyperthermia-range heat exposure (e.g., 39–42°C) that may be encountered in patients (Dewhurst et al., 2003) but from experimental studies in rodent brain where sensitivity to heat is thought greatest for this tissue, the threshold for temperature damage after experimental ischemic stroke, for example, is approximately 40°C (Kim et al., 1996). This contrasts with current opinion in human brain injury where even a small increase in neuronal temperature is thought harmful (McIlvoy, 2004). Currently the evidence is inconclusive in patients, at least for those with severe traumatic brain injury (Childs et al., 2010). High temperature is life threatening if heat stress worsens to heat stroke (Hart et al., 1980).

The clinical neurologic consequences of an excess of stored heat begins with tiredness and mental exhaustion (Nybo and Nielsen, 2001) and if heat retention does not abate, the risk of death rises.

In opening up discussion on body temperature we posit the question: is there a single value for body temperature? The answer is no. Our organ temperatures vary, albeit slightly in health, but more so in disease. Skin, the largest organ of the body, varies much more than internal temperature due to fluctuations in the temperature of the environment. Temperature also varies with time of day – the 24-hour circadian rhythm, lowest during sleep, within the hours of 04:00 and 06:00 and highest between 16:00 and 18:00 (Kräuchi, 2002). Not all circadian rhythms follow the same cycle; the circadian rhythm of cortisol, for example, begins to rise during sleep to reach a peak between dawn and early morning (Dijk et al., 2012).

Apart from the effect of physical activity, other factors which contribute to temperature variation include food intake, particularly diets high in protein (Frayn, 1997), emotional stress (Oka, 2015), and the menstrual cycle (Fukaya et al., 2017). Human biology therefore plays a significant modifying role in body temperature fluctuations over the course of the day. In the real world of the hospital ward, what can be taken from such knowledge? The first point for the clinician to consider is the importance of repeat measurement, checking the initial measure and a curiosity in questioning (and rechecking) a measurement which does not fit with the clinical picture, especially if there is a suspicion of the presence of disease, or even a faulty thermometer.

THE CONCEPT OF BODY SHELL AND CORE TEMPERATURE

A useful concept with which to approach an understanding of temperature is to view the body as an entity with a superficial shell and central core (Fig. 29.1). The core is essentially the source of heat production and the shell serves to regulate heat loss from the body.

The body shell

Skin, as our outer “shell” and covering, is in direct contact with the environment, whereas by nature of position inside the body, core organs are protected from extremes of ambient conditions (air temperature, humidity). The skin is therefore our thermal sensory and ultimately thermal protective organ.

The most important mechanism in human thermoregulation is conscious behavior. At a basic level we try to avoid two extremes of temperature stress: shivering and sweating.

If we are mobile, our first line of defense against hostile climatic conditions is to move away from a source of heat (or cold). We can also increase or decrease insulation (usually clothing) as necessary. The interdependence of skin thermoreceptors and behavioral thermoregulation is an integral first-line defense; the outer shell (skin) contributes to the stability of the internal temperature of core tissues. Neonates, having neither the ability to move any distance for themselves nor the independence to move away from external threats such as harsh temperature conditions, are reliant on others to protect them.

In the cold, this is where the biologic role of a specialized and metabolically active tissue, brown adipose tissue (BAT) is an additional protection, the main function being to produce heat (Gilsanz et al., 2013), because
Shivering thermogenesis is not yet fully developed. In the neonate, BAT is located in interscapular, supraclavicular, suprarenal, pericardial, and para-aortic regions, making up approximately 5% of body weight. BAT appears brown on inspection due to its rich supply of blood vessels. It is packed with mitochondria and has a key role in nonshivering thermogenesis. BAT contributes to a large part of resting metabolic heat production and helps counter heat loss brought about by the large surface area-to-volume ratio of the neonate that makes the young of mammalian species vulnerable to cold.

From a thermoregulatory perspective then, if we are able to move, we can protect ourselves because we are also able to sense changes in temperature in skin. Having a sense of satisfaction with the temperature of our surroundings is an individual perception. Most importantly, being comfortable, avoiding sweating and shivering, has evolutionary benefit, for both are energy-consuming processes.

Less demanding from an energy-consuming perspective are the physiologic mechanisms of thermoregulation where temperature can be controlled by adjusting blood flow to the skin. For example, skin facilitates heat loss by wet (evaporative) and dry (radiation, conduction, convection) routes to the environment. Heat is brought to the skin surface via the subcutaneous tissue to local skin capillaries. Skin acts as a heat exchanger between the body and environment. As skin is influenced by the temperature of the immediate environment as well as the temperature of blood supply, temperature variation is
considerable across surface regions. As a result, skin has been likened to a “thermal mosaic” (Henane et al., 1981) (Fig. 29.2).

Human skin circulation is controlled by two populations of sympathetic nerves: the sympathetic adrenergic vasoconstrictor system coexisting alongside sympathetic vasodilator nerves. The sympathetic vasoconstrictor and vasodilator nerves innervate the majority of skin blood vessels (in nonglabrous areas) but glabrous skin (palms, soles, lips) receives impulses from sympathetic vasoconstrictor nerves only. During exposure to cold, we see the effects of local cooling particularly at the extremities: hand skin appears white due to vasoconstriction and the retraction of blood from capillaries in the digits. Skin blood flow can fall to zero and skin temperature at the extremities trends towards environmental temperature (Fig. 29.3) (Charkoudian, 2003). As shell temperature falls, especially at the periphery (Fig. 29.1), the effect is retention of heat within the core.

In humans, especially at the lower limit of the thermo-neutral zone (often called the comfort zone) which in naked humans is about 28–30°C, heat production begins to rise and heat is conserved within the body. In addition to changes in vasomotor tone (constriction) of skin blood vessels there is a network of vessels, arteriovenous anastomoses (AVAs), which form direct connections between small arteries and small veins. The AVAs play a role in thermoregulation (Walloe, 2016).

AVAs are short vessel segments with thick muscular walls of large diameter and are abundant in the fingers and toes of glabrous skin. At the lower end of the thermo-neutral zone the AVA shunts remain closed and blood flow through them is near zero. AVA function becomes more important in extreme cold when the skin, due to retention of blood (and heat) to core tissues, receives almost no blood flow. The risk of cold injury to fingers and toes is high (frost nip, for example) but tissue damage is prevented by opening up of AVAs to bring about cold-induced vasodilation. Through cold-induced vasodilation the extremities are supplied with warm blood. This prevents tissue damage, so preserving skin viability. Cyclic periods of cooling and warming are called the hunting response (Lewis, 1930).

Blood vessels at the extremity, particularly the hands, are normally subject to a high degree of vasoconstriction even when the person is comfortably warm, but as environmental temperature rises, the increase in blood flow and temperature is almost entirely due to release of vasoconstrictor tone which allows the vessels to dilate (vasodilation) (Daanen, 1991); the skin becomes pink.

Fig. 29.2. Thermal image of infrared thermogram showing the variation in temperature across female abdomen as a “thermal mosaic.” Temperature key is indicated to the right of the image. Brightest regions indicate higher temperature and dark colors, lower temperature. The brightest (hottest) region is the umbilicus (Childs, C., unpublished data).

Fig. 29.3. Two hand thermograms, adult male, exposed to cold (A: 14°C) and warm (B: 22°C) ambient conditions to show the retraction of blood and heat from the digits (dark color on thermogram) and returning on exposure to an increase in air temperature. On exposure to cold, the thermal image appears as a “thermal amputation,” with demarcation of temperature change of digits compared with dorsum of hand. With return of blood and heat to the digits, the course of the major vessels from forearm to digits can be observed (Childs, C., unpublished data).
Skin temperature and perception of thermal comfort

The perceived state of being satisfied with surrounding air temperature (especially indoors) is called thermal comfort. Skin temperature is key to the perception of being comfortable with environmental conditions. A scale developed by Fanger (1973) has been used extensively in factories and offices to provide the optimum air-conditioning and comfort temperature for workers (Oseland, 1995). Being able to perceive temperature is mediated by a variety of primary afferent nerve fibers that transduce, encode, and transmit thermal information from skin to brain via pathways from brainstem, hypothalamus, thalamus, and insula cortex, where processing and discrimination of temperature sensation between warmth and cold occur.

Cutaneous thermoreceptors are sensory peripheral nerves and are classified on the basis of myelination and speed of the action potentials along the afferent nerve fibers. They are also further classified on the basis of their sensory role. Thermoreceptors respond to warming or cooling of skin (Lumpin and Caterina, 2007). C-fibers are mostly involved in perception of warmth but certain C-fibers also become activated during noxious cold (Park and Kim, 2013). By contrast, Aδ fibers respond to gentle cooling. The skin, being our largest sensory organ, provides the interface between deep body temperature and the environment (ambient temperature). It is at this border, between the external and internal environment, that skin thermoregulatory defense responses maintain thermal homeostasis (Romanovsky, 2014).

The physiology of temperature sensation has advanced in recent years with the discovery of receptor proteins located within free nerve endings in skin, the transient receptor potential (TRP) ion channels. The activity of these channels depends upon the temperature of their environment and they are essentially considered cellular sensors (Park and Kim, 2013) or even thermostat molecules (Jänig, 2015). TRP proteins are grouped into six families. Three families of TRPs are recognized as thermoreceptors, each with different temperature sensitivities and, whilst acknowledging overlap, their firing at different temperature sensitivities has confirmed their role in the molecular basis of thermoreception and thermoregulation that now shapes new models for thermoregulation (Jänig, 2015; Saito and Tominaga, 2017).

Of importance here is the still unresolved issue of whether TRP molecules as thermoreceptors function as thermostors or thermostats (Kobayashi, 2015). If thermostors, their role is primarily in thermal sensation, monitoring feelings of cold or heat and with messages relayed to the brain where the message is decoded. Alternatively, thermoreceptors may act as skin temperature thermostats (skin temperature regulator per se) to induce an efferent response to regulate temperature.

On balance, and with no consensus on the precise role of TRP molecules as thermosensor or thermostat, skin temperature represents a greater input to elicit responses to changes in the external thermal environment than does deep body temperature. Romanovsky (2014) proposes that one of the key thermoregulatory roles of thermal cutaneous signals is in providing an auxiliary feedback signal which allows for a rapid response to help in the regulation of deep body temperature where both negative and positive feedback to the thermoregulatory system operate (Romanovsky, 2014). In humans (as in all mammals) it has been a long-held concept that control of deep body temperature uses the primary (negative) feedback signal.

Cutaneous thermosensory signals play a greater role than previously considered. It is now clear that, with the discovery of TRP channels, expressed in primary sensory neurons, renewed interest in thermosensation and thermoregulation has resumed. Almeida et al. (2012), for example, report on the role of the TRP channel TRPM8, albeit in a study of rodents. Here they show that deep body temperature depends on cold signals arising from cutaneous TRMP8 channels. The TRPM8 channels are universal cold detectors in skin; they serve as thermosensors and drive thermoeffectors.

With greater knowledge of the molecular basis of peripheral thermoregulation comes possibilities for modulation of thermal perception and, possibly, applications for management of temperature abnormalities.

Core temperature

The body core is represented by deep tissues and organs. The organs with high metabolic activity (and thus greatest capacity to produce heat) includes heart, liver, and brain.

Core temperature is generally measured in hospital as part of a series of measurements of vital signs. Changes in core temperature are one of the most common clinical signs of disease in patients and may present as a rise (usually due to fever) or a below-normal temperature, as may occur during anesthesia, when mild hypothermia, 34–35°C, may occur during prolonged surgery. In practice, the approximation of core temperature is realized most effectively in critical care settings where the
need for continuous monitoring forms a part of the intensive care of patients and where the positioning of the temperature probe deep inside the body is justified on the grounds that alterations in core body temperature (high or low) may forewarn of clinical deterioration.

In adult trauma, one component to the rise in metabolic heat production that contributes to elevated temperature may rest with BAT, although this remains a subject of some debate. Whilst the persistence of BAT as a tissue in the adult has long been thought vestigial as an organ of thermoregulatory heat production, there is now evidence that substantial depots of BAT are detectable in disease states. Using 18F-FDG positron emission tomography in regions extending from the anterior neck to the thorax, there is some evidence that BAT is “switched on” (Cypess et al., 2009) in adults. The well-characterized increase in metabolic heat production and high fever after severe burn injury in children (Childs, 1997) may be mediated in part by activation of uncoupling protein in BAT (Yo et al., 2013).

Alterations in thermogenesis in disease and injury alter the temperature of the tissues of the body. The purpose of core temperature measurement is to obtain an accurate measurement of the organs and their blood supply. With the exception of the sublingual pocket (oral) measurement, the core sites used in routine clinical practice are essentially not core per se but approximation (often referred to as surrogate) measures of core temperature. In spheres of medicine where continuous measurement and monitoring of a patient’s temperature are of critical importance to survival, temperature sensors are most usually positioned within the body rather than the “surrogate” measures of skin folds of the axilla or groin.

**CLINICAL THERMOMETRY**

**Temperature measurement and monitoring**

By far the most common circumstances for either checking a person’s temperature or for considering repeat measurements is to detect deviations from normal, i.e., temperature values indicative of fever (regulated rise), hyperthermia (unregulated rise), or hypothermia (below normal temperature).

In children, for example, fever due to infections is the single most common complaint, reported in 30% of children presenting to the emergency department (Berkowitz, 2004). On the other hand hypothermia indoors is more common in patients recovering from anesthesia, in preterm neonates, and frail older people. For those who are exposed to low environmental temperatures outdoors (due to accidents associated with avalanche, cold immersion) accidental hypothermia (body temperature below 35°C) occurs as thermoregulatory effector mechanisms are outstripped by excessive heat loss to the environment. In alpine accidents, for example, deep hypothermia (core temperature below 28°C) presents a significant risk (66%) for cardiac arrest (Debaty et al., 2015).

Hypothermia can also accompany sepsis, a potentially fatal complication of severe infection. Septic patients with a low body temperature are predicted to have a poor outcome and are often treated by rewarming due to the opinion that hypothermia represents failure of thermoregulation. Contrary to current opinion, however, hypothermia in sepsis has recently been shown to be a transient, self-limiting, nonfatal sequela of sepsis. Body temperature, if left untreated, rarely falls below 34°C. This finding supports the notion that temperature regulation persists in sepsis-related hypothermia, as it does in fever, bringing new perspectives on human thermoregulation at the extremes of the physiologic temperature range (Fonseca et al., 2016).

In deciding the method of core temperature monitoring we may consider the relevant factors central to selecting the most valuable part of the body to measure and for inclusion in the temperature management protocol. Additionally, we consider the most appropriate thermometer type. For sick patients, there is a need for accurate and precise measurement because spurious values can influence clinical management and disease prognosis. Another consideration for treatment protocols is the optimal method: whether to use invasive, minimally invasive, or noninvasive thermometers as well as measurement frequency, spot measurements, or continuous monitoring. The decision will ultimately rest with the nature of the patient’s presenting condition and the equipment available within the institution as well as the expertise and understanding of the need for robust measurement from the clinician. Where routine temperature-monitoring protocols fall short of optimum reliability and accuracy, clinicians, acting as the patient’s advocate and with a full understanding of the options for clinical thermometry, may lobby for a change in routine temperature measurement protocols to provide the most accurate information upon which treatment decisions can be based.

**TECHNIQUES FOR SKIN TEMPERATURE MEASUREMENT**

Whilst thermistor or thermocouple sensors are still available for use for skin surface measurement, measuring skin temperature is, in many ways, much more efficient if the need for taping sensors on to the skin can be avoided. Here, noninvasive, noncontact skin thermometry is ideally suited and provides an easier way for regular monitoring. The most commonly used noncontact method in clinical practice is the infrared thermometer. Typically, the device houses an infrared detector and a series of electronics which convert infrared energy to temperature units and this is displayed on an integral display screen.
Techniques for Core Temperature Measurement

There have been numerous publications seeking to find a true representation of core temperature but what organ is considered to be the gold standard for core temperature? The assumption is that the temperature of the “thermoregulatory center” itself, the hypothalamus, a small area of gray matter, deep within the center of the cerebral hemispheres (the diencephalon), represents a true measure that can be realized as core temperature. Brain tissue is shielded from the environment due to its location within the skull and, along with the constant bathing of the brain by incoming arterial blood, at a constant and rapid rate, it would seem reasonable to posit that brain and arterial blood temperature would be comparable. However, for all practical purposes, due to the position of this tiny region, we do not aim to measure hypothalamic temperature but instead settle for one of several representative core sites.

The site selected will ultimately depend upon the need for accuracy and reliability, particularly in sick patients. Examples of core temperature sites include rectum, esophagus, pulmonary artery, bladder, brain, sublingual pocket (within the oral cavity) and, largely limited to research, the digestive tract (via a radio telemetry pill). Other more widely used sites such as the tympanum (accessed via the auditory canal) and skin overlying the temporal artery do not require insertion of the device into the body and are therefore essentially a “surrogate” measure of core temperature. There is a large literature devoted to understanding the reliability and reproducibility of surrogate measures for core temperature. However, despite an interval of over 60 years and advances in thermometry, it is noteworthy that, in health at least, normal core temperature in different cohorts remains, on average, remarkably consistent at 36.9°C irrespective of gender, age, and body mass (Tables 29.1 and 29.2).

Thermometer Devices

Digital thermometers

With the demise of the mercury-in-glass thermometer in routine clinical care on safety grounds, new types of thermometer have come to the forefront of modern thermometry. The most well recognized in routine practice is the hand-held digital thermometer. Other types of digital temperature-monitoring systems are incorporated into dedicated bedside temperature-monitoring systems at individual bed spaces of the intensive care and high dependency units or in portable standalone patient-monitoring systems, as used in the ambulance service.

Temperature probes and monitoring systems of the type used in critical care or anesthesia where the sensor per se is placed and fixed in situ within the body (e.g., esophagus, pulmonary artery, brain ventricle, and brain white matter) usually have the temperature sensor

Table 29.1

Body core temperature measured at different sites in healthy adult subjects

<table>
<thead>
<tr>
<th>Site</th>
<th>Subjects</th>
<th>N=</th>
<th>Range (°C)</th>
<th>Mean</th>
<th>Median</th>
<th>Authors/Year published</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brain</td>
<td>Adult</td>
<td>8</td>
<td>35.8–36.7</td>
<td>36.5</td>
<td></td>
<td>Childs et al. (2007)</td>
<td>1HMRS-4 single voxels (deep white matter)</td>
</tr>
<tr>
<td>Brain</td>
<td>Adult</td>
<td>20</td>
<td>37.0–38.0</td>
<td>37.4</td>
<td></td>
<td>Rango et al. (2015)</td>
<td>1H MRS thermometry-visual cortex</td>
</tr>
<tr>
<td>Rectal</td>
<td>Adult</td>
<td>46</td>
<td>36.7–37.1</td>
<td>37.1</td>
<td></td>
<td>Tanner (1951)</td>
<td>Healthy males at rest</td>
</tr>
<tr>
<td>Rectal</td>
<td>Adult</td>
<td>53</td>
<td>36.7–37.1</td>
<td>36.9</td>
<td></td>
<td>Horwath et al. (1950)</td>
<td>Healthy subjects: 38 female, 16 male</td>
</tr>
<tr>
<td>Rectal</td>
<td>Adult men</td>
<td></td>
<td>36.7–37.5</td>
<td>36.9</td>
<td></td>
<td>Sund-Levander et al. (2002)</td>
<td>Healthy men and women: systematic review summary of 27 studies of which 9 reported rectal temperature values (1935–1999)</td>
</tr>
<tr>
<td>Rectal</td>
<td>Adult women</td>
<td></td>
<td>36.8–37.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>“Core” (24 h telemetry)</td>
<td>Adult normal-weight</td>
<td>35</td>
<td>36.4–37.3</td>
<td>36.93</td>
<td></td>
<td>Heikins et al. (2011)</td>
<td>Average 24-h daily temperature measured by swallowing wireless temperature-sensing capsule</td>
</tr>
<tr>
<td>“Core” (24 h telemetry)</td>
<td>Adult-obese</td>
<td>46</td>
<td>36.5–37.4</td>
<td>36.97</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Oral (sublingual pocket)</td>
<td>Adult- healthy ≥ 60 years</td>
<td></td>
<td>36.1–36.6</td>
<td>36.3</td>
<td></td>
<td>Lu et al. (2009)</td>
<td>Systematic review – 16 studies included</td>
</tr>
</tbody>
</table>
Table 29.2
Measured temperature range in hospital patients: understanding the relationship between different “true” core tissue temperatures and “surrogate” sites (gray highlighting) with author publications indicated in parentheses. To read results of direction of temperature site differences (polarity), values are: reference site (left column) minus comparator site (top row). Negative values indicate reference site is lower than comparator site.

<table>
<thead>
<tr>
<th>Thermometer readings at different body sites in adult disease</th>
<th>Differences (°C)</th>
<th>Range: (mean) $\text{sd}^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core body</td>
<td>Comparator</td>
<td></td>
</tr>
<tr>
<td>Reference</td>
<td>Rectum</td>
<td>Bladder</td>
</tr>
<tr>
<td>Brain</td>
<td>–0.13 to 0.05 (&lt;0.04) (Childs et al., 2007)</td>
<td>–0.18 to –0.16 (&lt;0.17) (Suchiro et al., 2011)</td>
</tr>
<tr>
<td>Pulmonary artery</td>
<td>–1.1 to 1.9 (&lt;0.07) (Lefrant et al., 2003)</td>
<td>–1 to 1.0 (&lt;0.21) sd 0.20 (Lefrant et al., 2003)</td>
</tr>
<tr>
<td>Temporal artery</td>
<td>–1.01 to 0.95 (&lt;0.03) (Singler et al., 2013)</td>
<td>–0.47 to –0.41 (&lt;0.44) (Stelfox et al., 2010)</td>
</tr>
</tbody>
</table>

$^{a}$sd given where available.
housed within the tip of the sensor element (implantable probe). The probe may be constructed for a single parameter (temperature) or, as in the newer, advanced monitoring systems, there may be two or more measurement parameters. For example, the multiparameter sensors available commercially for neurocritical care (Fig. 29.4) provide a temporal profile of multiple parameters, one example being temperature, pressure, and brain tissue oxygen content.

Other options include multiple tissue chemistry in a single probe and, if additional probes are used, a complete profile of chemistry, temperature, pressure, and oxygen content can give the clinician a detailed profile of the physiologic and pathophysiologic changes occurring in the injured tissue. These sensors have been shown to be reliable over an extended period of neuromonitoring (Childs et al., 2014).

Figure 29.4 illustrates the value of multiple measurement parameters providing information to the clinician and shows, in this example, the correspondence in temperature at two brain sites. It also shows the near exact measurements obtained using a rectal probe and refutes the often-reported lag in temperature between rectal values and other core temperatures, indicating that rectal temperature, in the main, provides a reliable and reproducible surrogate for brain temperature where insertion of sensors in the brain is justifiable clinically (Childs et al., 2014).

The type of sensor used at the tip of the temperature measurement probe (or in dedicated hand-held thermometers) falls broadly to two types: thermocouple or thermistor. A third digital thermometer type, the resistance temperature detector, usually using platinum as the resistance metal (platinum resistance thermometer), is more often used in the laboratory for calibration of thermistors and thermocouples. Platinum resistance thermometers are stable over long periods, and are the most accurate sensors, especially in industrial applications. Platinum resistance thermometers cover a temperature range of \(-200^\circ\) to \(800^\circ\C\) (http://www.Enercorp.com/temp/Thermistors_comparison). They have a fast response time (Mangum et al., 2001). The disadvantage is in their cost.

In the clinic it is not obvious, looking at a thermometer or bedside device, to know the type of measurement sensor without first checking the product information sheet, for temperature sensors may be engineered using a thermocouple or thermistor (HMSO, 1981).

**Thermocouples**

Thermocouples are sensitive to small changes in temperature. The instrument consists of two different metal wires, joined at one end. The metal wire pairs generate a voltage difference between the two wire ends; voltage increases with temperature. Critical to the measurement is a calibration of known thermolectric voltage corresponding to the temperature difference between the two wire ends. An example of a thermocouple used in a hospital is the skin thermocouple. The disadvantages of the thermocouple is that the materials used can corrode over time and affect sensor accuracy.

**Thermistors**

Thermistors, on the other hand, operate in a different way to thermocouples. They are devices with resistance, changing with temperature variation depending upon the materials used. Thermistors are of two types: the first is the negative temperature coefficient (thermistor resistance is inversely proportional to temperature) such that resistance decreases as temperature increases. The second type (positive temperature coefficient) are thermistors where resistance is directly proportional to temperature. For example, when resistance increases, temperature increases (or vice versa). The most common type of
thermistor operates using the principle of a negative temperature coefficient. This type of thermistor is constructed using oxides of iron, copper, or nickel.

The advantages of thermistors are that they are long-lasting and accurate. They are not as widely used as thermocouples for temperature measurements above 250°C because accuracy and linearity of measurement are best at a temperature span of 100°C and with upper temperature limit not exceeding 200°C.

**Infrared thermometry**

Thermometers using infrared technology are now widely available in medicine (Ring and Ammer, 2000; Diakides and Bronzino, 2008). The basic scientific principle underlying the operation of infrared thermometers is in the design of the detector able to receive radiation emitted from the body within the infrared region of the electromagnetic spectrum. The shortest-wavelength, highest-frequency, highest-energy type are gamma rays. Short wavelengths are used in medicine in positron emission tomography scanners and in gamma cameras and gamma knives in neurosurgery. At the other end of the spectrum are long (radio) waves.

Infrared radiation lies about halfway along the electromagnetic spectrum between the visible and microwave portions. Infrared radiation is not visible; human eyes are designed to detect electromagnetic radiation in the visible light spectrum only. The eye perceives light at wavelengths of approximately 0.4–0.7 μm (Usamentiaga et al., 2014). However, if night goggles are used, for example, by the military to detect infrared light, we are then able to "see" heat emitted from skin and objects which emit heat energy (radiation). The heat we sense from sunlight, a fire, or radiator is all radiant energy emitted in the infrared spectrum.

Typically, infrared thermometers for use in hospital detect wavelengths between 8 and 14 μm. As the primary source of infrared radiation is heat or thermal energy (radiation), any object which is above absolute zero – – 273.15°C or 0°K (Mangum et al., 2001) – emits radiation in infrared and this includes objects that are very cold, e.g., ice cubes, snow. Infrared thermometers convert radiation energy to measurable units of temperature (e.g., °C, °F).

**Thermography**

Whilst infrared detector systems provide the clinician with information about temperature values and thus act as a thermometer, infrared thermography provides additional information as a picture which provides the user with a skin surface temperature map, usually in one of a number of color palettes (Figs 29.2 and 29.3). Typically, infrared thermography (or digital infrared thermal imaging) uses a special type of camera containing sensors which detect thermal (radiant) energy (Diakides and Bronzino, 2008).

The energy is displayed as an image composed of pixels. Pixel resolution can vary; cheaper cameras have a resolution typically of 60 × 120 pixels. The cost increases with resolution, the highest for affordable cameras being 640 × 480 to 1280 × 1024 pixels across the image. By convention, the hotter the image, the brighter the color displayed on the camera screen. Lowest temperatures are displayed as dark colors (Figs 29.2 and 29.3).

Thermal cameras do not emit any form of ionizing (gamma rays, X-rays, or microwaves) radiation known to be damaging to cells. The systems are entirely passive, detecting radiant energy only. Thermography is noncontact and safe and used in medicine for visualizing the distribution of temperature across an exposed surface of skin (Ring and Ammer, 2000; Selvan and Childs, 2017). It has the capability for monitoring thermal abnormalities which accompany disease and injury where blood flow and metabolic changes bring alterations in surface temperature. The use of thermal imaging in routine screening however has its limitations as infrared scanning is restricted to surface temperature only – the skin. In most situations of illness and disease which present to the clinician, the skin is seldom the hottest region of the body. In fever screening it is widely acknowledged that the internal core organs are the hottest regions of the human body.

**Thermography in fever and infection screening.** The success of fever diagnosis using noncontact infrared thermography of the skin surface is inevitably influenced by choice of target site. In view of the evidence that skin is neither constant nor uniform and greatly influenced by ambient conditions, the choice of skin location must inevitably be a significant factor for the target region of interest which best reflects body temperature.

**Mass screening**

With emerging infectious diseases resulting in global outbreaks such as the severe acute respiratory disease pandemic in 2003, swine flu pandemic (H1N1) in 2009, and Ebola epidemic (2014), border entry and exit screening measures (Bitar et al., 2009) were imposed at international airports, seaports, and country borders (Chiu et al., 2005). Since these infectious diseases are accompanied by fever, infrared thermal imaging of travelers was introduced in many countries with the objective of identifying febrile passengers. Sensitivity of fever for detecting H1N1-2009 cases upon arrival was estimated to be 22.2% among 9 confirmed H1N1-2009 cases, but 55% of the H1N1-2009 cases had taken antipyretic medication upon arrival. Sensitivity and specificity of infrared thermography using thermal scanners to detect raised temperature ranged from 50 to 70% (sensitivity) and 63 to 81% (specificity). The positive predictive value appeared to be as low, 37–68% (Nishiura and Kamiya, 2011).
Accuracy of the thermal camera as a thermometer together with the reliability of the temperature value as a sensitive marker of the infectious disease (especially with confounding factors such as ingestion of antipyretics) may account for poor performance of thermal cameras to detect febrile passengers at border crossings. However, as passengers pass through border controls, there is potential benefit of thermography to operate as a first-line screening tool along with passenger self-report health questionnaires. Ear (tympanic) measurements can then be used for a second-level screening either for those with positive fever self-reports or for those who are detected as febrile (temperature above 37.8°C) on thermography, if the thermal camera detects a rise in temperature.

One of the key targets of thermography is the forehead but other sites may be more reliable. One area under investigation is a small region on the face where temperature is highest; the skin between the medial aspect of the orbit and the nose, the inner canthus (Fig. 29.5). A rich network of vessels supplies this small area, the supply originating with ophthalmic artery (supratrochlear branch) (Erdogmus and Govsa, 2006). Changes in skin temperature during fever are reported to be within 0.5°C of the brain temperature measured deep within white matter of the frontal lobe (Childs et al., 2012).

Moving from applications of thermography in the screening of populations of travelers as a public health initiative, there is also evidence that thermography of the skin can be employed for specific diagnostic potential. Thermography has been used in a number of clinical applications; as a potential alternative to breast cancer diagnosis (Cruz-Ramirez and Mezura-Montes, 2013); providing an alternative to the ionizing radiation of mammography, it is used in the identification of perforator vessels in deep inferior epigastric perforator lower abdominal flaps for breast reconstruction (Weum et al., 2016) and in self-monitoring of patients at high risk of diabetic foot (Sibbald et al., 2015).

Thermography and surgical site infection screening

Infection of the surgical site is a major cause of morbidity in patients expected to survive their surgical procedures. In colorectal surgery, infection rate is double (10%) that in general surgery, yet there remains no independent diagnostic wound infection technology. Currently, assessment is made using wound scoring systems; the Centers for Disease Control and Prevention criteria (Horan et al., 1992) include purulent exudate, often a late indication of wound infection. Thermography is now being explored for diagnostic potential in new applications, such as surgical site infection and screening (Siah and Childs, 2015; Childs et al., 2016) where stratification of patients early after surgery to high or low risk of later postoperative wound infection may bring new approaches to postoperative antibiotic prescribing.

MRS and imaging for absolute temperature measurement

Moving away from conventional thermometry, a new approach to internal temperature measurement can be undertaken without the need to insert probes or sensors into the body. Scanning a patient in a 1.5- or 3-T magnet (scanner) is currently one of the most advanced systems for noninvasive internal body temperature measurement in medicine. Techniques have been developed for both nuclear MRS and magnetic resonance imaging (MRI) of internal temperature and the technique is being used in stroke (Karaszewski et al., 2013).

MRS and MRI have been used in clinical research to obtain absolute temperature values (°C) using a method based on the (1H) proton chemical shift difference between resonances for water and a reference proton within the target organ. In brain, N-acetylaspartate, an abundant brain chemical, detectable in 1H brain spectra, resonates at 2.01 ppm within the physiologic temperature range expected during health and critical illness. This brain metabolite is independent of pH, is physiologically stable, and makes for an ideal reference.

The principle for single-voxel and regional MR temperature measurement is based on the knowledge that the water chemical shift has an almost linear dependence on temperature (Cady, 1990). 1H water resonance appears at 4.7 ppm. However, because the spectral peak for water is high, the signal is suppressed and this allows 1H peak for water and for other molecules to be identified across the spectra. The signal difference between molecule

![Fig. 29.5. Infrared thermal image of the face of a healthy subject showing temperature of region of the inner canthus. Gray regions represent the highest temperature pixels of the thermogram. Color temperature key is given to the right of the image. Right (R) and Left (L) inner canthus; the pixels colored “grey” are the highest values in this thermogram; R at maximum 35.5°C and L, highest value, 35.2°C. (Childs and Low, unpublished data.)](image-url)
resonances for water, being temperature-dependent and proton reference (temperature-independent), is converted to temperature using a calibration curve (Fig. 29.6). Temperature can be obtained in single voxels at different sites within an organ or as temperature maps across an organ slice (temperature mapping). The use of the proton ($^1$H) chemical shift of water referenced to a variety of endogenous metabolites to probe absolute internal temperature overcomes the limitations of focal temperature measurement, i.e., one measured temperature point only within an organ. It should be borne in mind, however, that, given the potential for this method of temperature measurement in medicine, it is important to relate the measured frequency shift with a reliable traceable temperature reference so that temperature measured is accurate to traceable measurement standards (Vescovo et al., 2013).

**Fig. 29.6.** Schematic of the technique for absolute human brain temperature measurement. Magnetic resonance spectroscopy (MRS) and imaging (MRI) can be performed at 1.5 and 3 T magnet strength. Using axial T2-weighted images, multiple brain slices are acquired for anatomic reference and to select positions of single-voxel proton ($^1$H MRS) positions (indicated by four black boxes). Spectral peaks for water (temperature-sensitive) are shown at 4.7 ppm and for chemical reference ($N$-acetyl aspartate, NAA) spectral peak is at 2.0 ppm. Analysis of spectra, employing a line shape-fitting (LF) method, calibration curve of the chemical shift difference between the two spectra peaks, yields a value of absolute temperature ($^\circ C$). (Summary schematic based on methods described in Childs et al., 2007.)

In many ways, the greatest activity in the investigation of normal body temperature arose from the early studies of the 1950s, particularly with the interest in new, now (with the lapse of time) conventional techniques for clinical thermometry – tympanic membrane temperature, for example. In recent times and as new technologies have emerged, such as telemetry for continuous 24-hour monitoring of temperature and $^1$H MRS and imaging for measurement of organs such as brain, previously impossible to access in vivo, we have sophisticated instruments available to measure temperature at multiple sites. From Table 29.1 we can appreciate that deep body temperature measured by different and independent technologies is in keeping with earlier reports of body temperature measured by different thermometers and, in different healthy cohorts. For example, the single study by Horwath et al. (1950) provides values for rectal temperature in agreement with a consensus achieved by systematic review of the literature undertaken by Sund-Levander et al. (2002), over 60 years later. So, we might agree that, in health at least, the textbook

**KNOWLEDGE TRANSLATION**

It is clear from a theoretic discussion of body thermal compartments (core and shell), the variety of different temperature measurement instruments available, and the emergence of advanced internal thermometry technologies, that the topic of body temperature embraces several different conventional and novel perspectives. Advances in clinical thermometry have brought both new understanding as well as new questions to modern medicine. When we seek to provide a unifying solution using review of the literature, whether of single studies, systematic review, or meta-analysis, we are still without an absolute value for normal body temperature, although in health it would appear that for different adult populations studied over many years human temperature averages at 36.9$^\circ C$. However, in disease, and because different people respond differently in terms of the temperature gain (or loss) brought about during inflammatory and disease processes, it is clear that different thermometers placed at different body sites give different measurement values. Predicting temperature of one site from another site is likely to be unreliable.

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statement that deep body temperature is approximately 37°C is correct. On the other hand the gold standard for body temperature, assumed to be brain could, in the past, only be assumed from measurement of temperature at the tympanum (Benzinger, 1969), a site now considered a rather unreliable method for estimation of core (and so brain) temperature measurement (Craig et al., 2002).

Now that we can measure absolute temperature using nuclear medicine techniques and applications, there is the opportunity to advance our understanding of human homeothermy because knowledge of brain temperature in health (and also disease) is still a niche area of investigation.

A significant advance in thermometry has been in our ability to integrate body temperature over the course of a 24-hour cycle using telemetry and digestible temperature-emitting pills. Here we can see correspondence between the average daily temperature and measures for both rectal and core body (digestive tract) sites. This work provides further evidence of the value of rectal temperature, even though it is often maligned as lagging behind other core sites. It would be reasonable to conclude that core temperature in healthy humans, irrespective of body mass, is 36.9°C. In disease, the impact of numerous inflammatory, injurious, neoplastic processes on core and skin temperature continues.

CONCLUSION

Advances in technology have brought new approaches and possibilities to the scientific pursuit and quest to understand the mechanisms and control of human thermoregulation. We have moved forward in the last 20 years such that we may, in the future, plan for noninvasive, accurate diagnostic imaging of the temperature of body surface structure as well as hard-to-measure organs and tissues shielded from the external environment. One of the major challenges in the development of new technologies will be cost–benefit. Only by appreciating and understanding the value and significance of temperature change in disease, and embracing the previously unknown potential of organ-specific changes in temperature values to forewarn as a clinical biomarker of disease and clinical deterioration, will a sound case be made to justify investment in novel temperature technologies.

REFERENCES


