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## **The significance of core temperature –** Pathophysiology and measurement methods



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## Pathophysiology and measurement methods

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# 1 Preface

For the past several decades, the significance of core temperature and the subject of thermal management, i.e. the maintenance, therapeutic adjustment and precise measurement of a patient's core temperature with regard to anaesthesia and, to a lesser extent intensive care medicine, have not been fully appreciated. In terms of measurable parameters in anaesthesia and intensive care patients, the importance of core temperature was often overlooked. This is partly due to the fact that the parameter core temperature appeared to be somewhat trivial and hardly innovative. The repercussions of this view can be felt up to this day, even though the importance of core temperature was demonstrated by the work of the thermoregulation pioneer Dr Daniel Sessler around 25 years ago.

Among other things, Dr Sessler was able to show the relationships between anaesthesia and thermoregulation as well as the influence anesthetic agents have on the autonomic thermoregulatory thresholds, the thresholds for vasoconstriction, shivering and perspiration. The rapid initial decrease in body temperature following induction was shown to be a result of the redistribution of warm core blood to the periphery as a result of vasodilation. Around ten years later, researchers in Sessler's group pointed to an additional hitherto unrecognised aspect of thermoregulation and were successful in demonstrating its significance: accidental hypothermia was more than just an unpleasant side effect of anaesthesia performed without sufficient thermal management. Indeed, accidental perioperative hypothermia has far-reaching consequences for long-term patient outcome. Accidental perioperative hypothermia increases blood loss, the incidence of infection, the rate of cardiac-related complications and length of hospital stay. Thus, active patient thermal management became part of outcome-oriented, evidence-based practice in anaesthesia departments around the world. In recent years, the maintenance of perioperative normothermia has become part of a so-called pay-for-performance initiative in the USA and receives financial support from health insurers. Other increasingly important aspects of core temperature have come into the spotlight in the last few years – therapeutic hypothermia following resuscitation or neonatal asphyxia has found its way into the guidelines of respective associations.

In spite of all these developments which demonstrate the central significance of core temperature in anaesthesia and intensive care medicine, one subject is still often belittled: the measurement of core temperature. Primitive thermometers, the inaccuracy of which has long been shown by a number of studies, continue to be used. Thermoregulatory therapy continues to be practised without measurement of therapeutic success or feedback – active perioperative warming without the use of core temperature measurements. This may be partially due to the fact that the seemingly simple measurement of core temperature in the clinical setting is a highly complex subject involving a large number of measurement locations, numerous implementation possibilities and, last but not least, the high level of variation and the possible invasiveness of the measurement method. The development and introduction of a core temperature measurement method which combines the advantages of very minimal invasiveness with a high level of accuracy at a reasonable price is an important step in the ongoing development of thermal management. In recent years, patient thermal management has gained a great deal of relevance. New, innovative measurement methods for core temperature serve to support this development and allow non-invasive yet precise feedback on the many evidence-based thermoregulatory therapy forms, helping to move toward the goal of improving patient outcome.

This booklet is intended to provide the reader with a concise, comprehensive overview of patient thermoregulation, the development and the current state of core temperature research and new developments on the horizon of core temperature measurement technology.



Stefan Quast  
Product Manager  
Dräger Medical GmbH



Dr Oliver Kimberger  
Senior Physician and Research Coordinator  
Dept. of General Anaesthesia and  
Intensive Care Medicine,  
University Clinic of Vienna



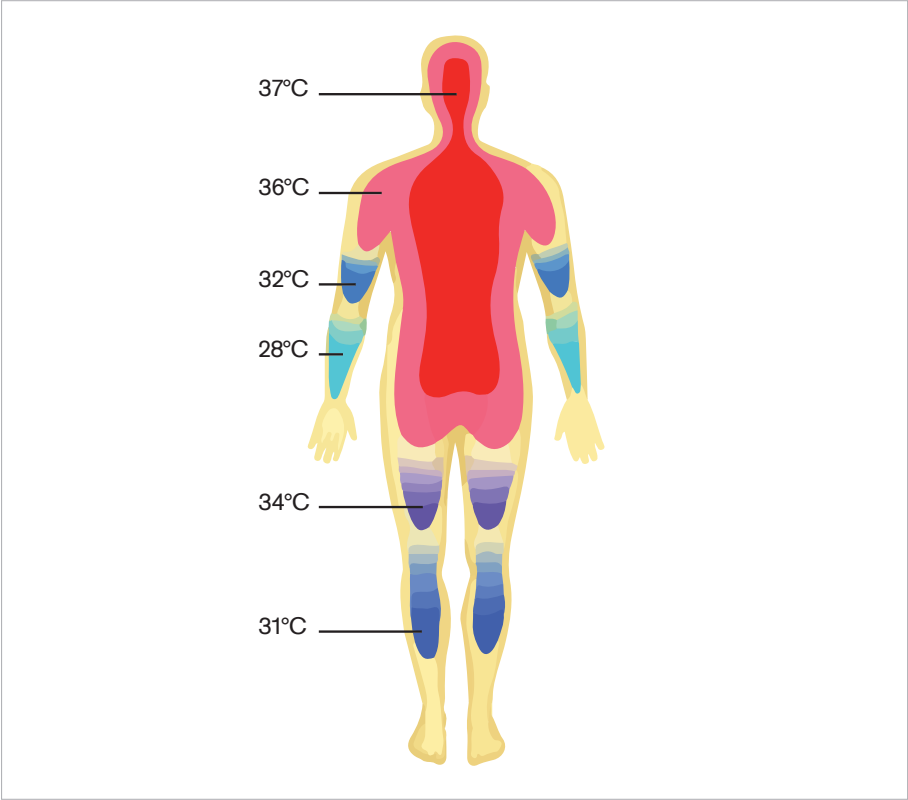
## 2 The nature of body temperature

### 2.1 TEMPERATURE AND WARMTH AS A PREREQUISITE FOR LIFE

Temperature is a physical dimension – and a basic prerequisite for all forms of life. The physical characteristics of matter are temperature-dependent. Even small variations can cause significant changes, such as those seen during the transformation from one aggregation state to another. The metabolisms of living organisms can be greatly influenced by temperature. Temperatures which are too high or too low can change metabolic rates, perturb organ function and cause tissue damage. Thus, body temperature and the temperature of the body's surroundings are of vital importance for life and health.

### 2.2 THERMOREGULATION

The regulation of body temperature is among the most important functions of any organism. The body temperature is a vital parameter, just as vital as respiration rate, heart rate or blood pressure. The thermoregulatory centre is located in the hypothalamus. Here, information from other regions of the brain, spinal cord, tissues and peripheral thermal sensors in the skin is processed. To achieve equilibrium between heat generation and dissipation, both conscious behavioural changes (i.e. putting on clothes) and autonomically driven mechanisms are called upon. These include perspiration and vasodilation to control overheating as well as shivering (thermogenesis) and vasoconstriction to prevent undercooling. When healthy, the human organism regulates core body temperature to within  $\pm 0.2^{\circ}\text{C}$  of the normal value. [1] [2] [3] [4]



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Fig. 1: Body core and periphery

### 2.3 CORE TEMPERATURE

Although temperatures in the peripheral regions of the body and extremities vary depending upon environmental conditions, the body's core, consisting of deep tissues, internal organs and the cerebrum, remains practically constant under normal conditions. The range of external temperatures at which core temperature can be maintained without the aid of shivering or sweating is known as the thermoneutral zone, and runs between 27 and 32°C for a naked adult human at rest. [2] [5] [6] [7]

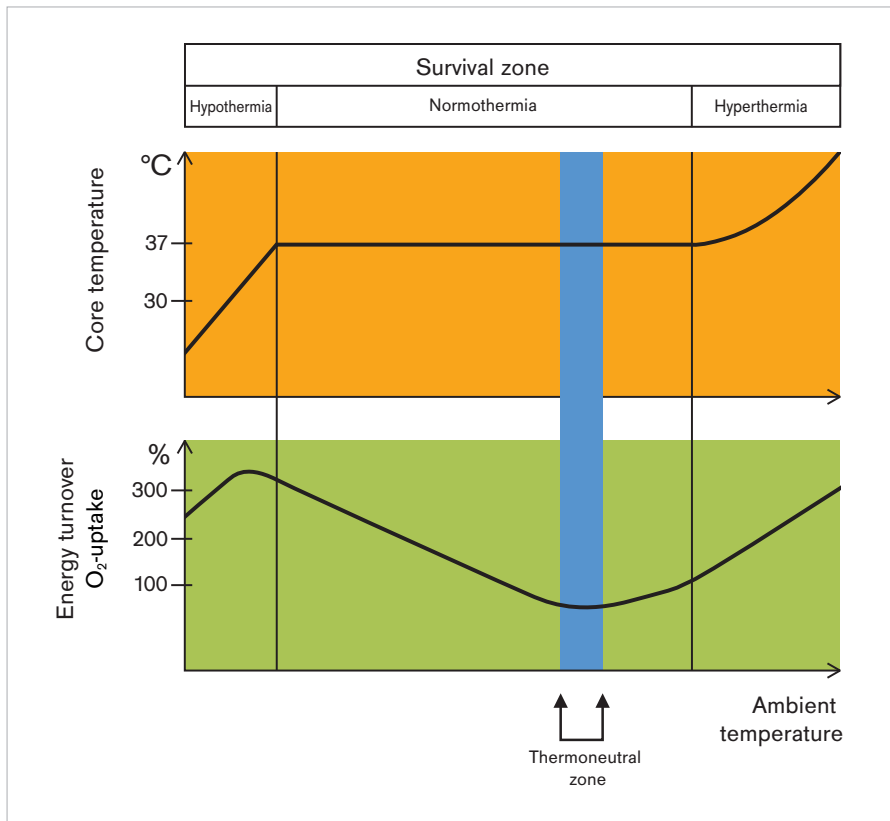
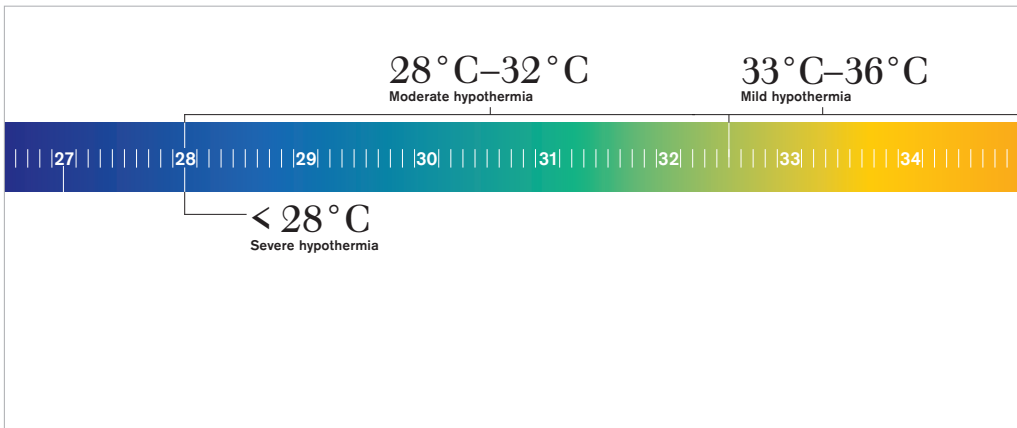


Fig. 2: The thermoneutral zone

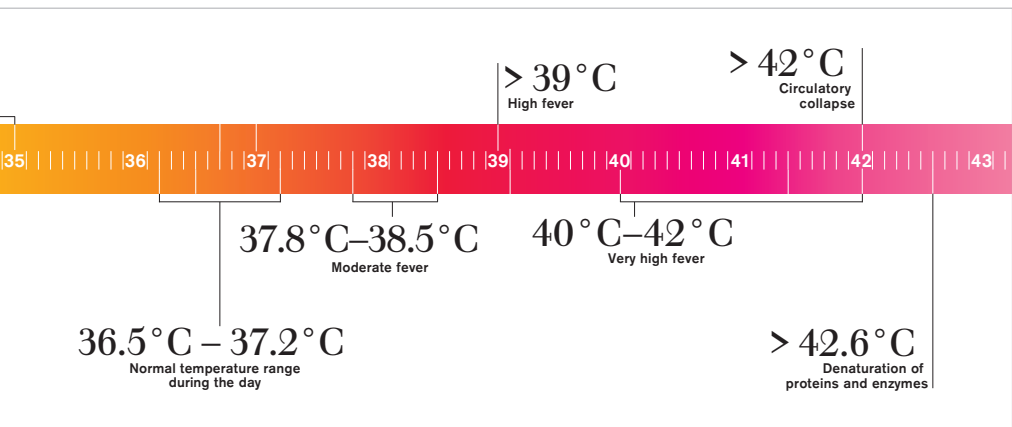
The normal range for core temperature is between 36.5 and 37.2°C, depending on the definition. Core temperature does, however, vary according to the time of day. In this circadian function, it is lowest in the early morning and reaches a maximum in the afternoon. The female menstrual cycle is also associated with regular swings in core temperature. Additionally, physical fitness, acute stress, age, alimentation and sleeping behaviour all influence core temperature. [2] [3] [4] [6] [8] [9] [10]

Harmful external influences such as infections and certain medications cause the human organism to react with an increase in core temperature. Following cardiac arrest, head trauma or stroke, an increase in core temperature is often observed. In order to interpret temperature values correctly in clinical settings, a profound knowledge of natural variation and the normal limits is necessary. [4] [6] [11]



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Fig. 3: Temperature spectrum of the human organism



## 3 Hypothermia

### 3.1 DEFINITION OF HYPOTHERMIA

Hypothermia refers to the cooling of the body beyond the normal temperature range. In practice, a limit of 36 °C is normally accepted. Below this value, organ function begins to deteriorate.

Temperatures between 36 to around 33 °C are considered mildly hypothermic. The body reacts with thermoregulatory mechanisms such as shivering and vasoconstriction. In addition, symptoms such as increased heart rate (tachycardia), increased respiratory rate (tachypnoea), coordination disturbances (ataxia), apathy, and a reduction in circulating blood volume (hypovolaemia) appear. Moderate hypothermia, or temperatures between 32 and 28 °C, cause respiratory depression (hypoventilation) slow pulse (bradycardia), decreased blood pressure (hypotension), reflex suppression (hyporeflexia), enlarged pupils and an ever-increasing loss of consciousness. Shivering ceases. At even lower temperatures (severe hypothermia) the human organism reacts with circulatory and respiratory collapse. [2] [6] [7] [12] [13] [14]

### 3.2 CAUSES AND TYPES OF HYPOTHERMIA

Temperature	Classification
> 42.6°C	Denaturation of protein
40–42.6°C	Thermoregulatory failure, heat stroke
37.8–40°C	Fever, hyperthermia
36–37.8°C	Normothermia
33–36°C	Mild hypothermia
28–32°C	Hypothermia, reduced metabolism, respiratory depression, loss of consciousness
< 28°C	Severe hypothermia, thermoregulatory failure, ventricular fibrillation, rigor, non-reactive pupils, bradycardia, cardiac arrest

Fig. 4: Effects of changes in body temperature according to [6]

Hypothermia can occur accidentally or as a result of controlled therapeutic intervention (therapeutic/protective hypothermia). Outside the clinical setting, hypothermia is usually the result of an accident in which the victim is exposed to cold over a longer period of time (i.e. cold environments, swimming accidents, falls through surface ice). In the hospital, pharmaceuticals and surgical procedures can cause accidental hypothermia. Although active patient cooling has comparable physiological consequences, it occurs under controlled conditions and its intent is protective or therapeutic in nature.

### 3.2.1 PERIOPERATIVE HYPOTHERMIA

Even during preparation for a surgical procedure, the patient often experiences inadvertent cooling. Low ambient temperatures and little or no clothing promote this unintentional loss of heat. Initially, the body successfully compensates for this loss with the help of thermoregulatory mechanisms. Peripheral vasoconstriction results in cooling of the outer body shell while core temperature remains stable. The administration of anesthetic agents delays the body's own regulatory mechanisms (see fig. 5 and 6). During general or spinal anaesthesia, further cooling begins in a process involving three phases (see fig. 7).

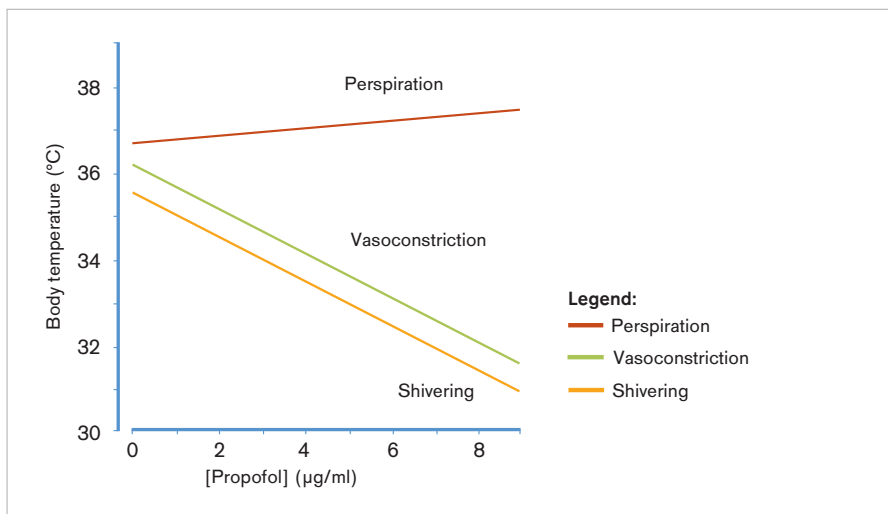
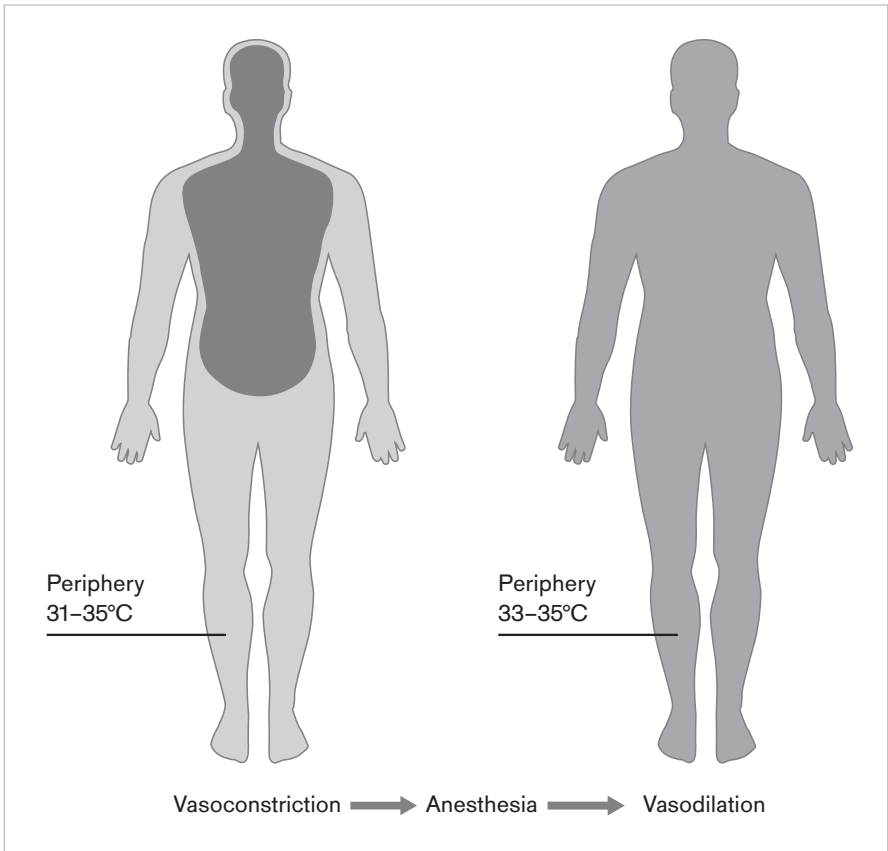


Fig. 5: Shifts in activation thresholds of thermoregulatory mechanisms caused by anesthetic agents according to [4]

Upon detailed examination, the perioperative patient without active warming experiences the following: most anesthetic agents cause vasodilation. Cold blood from the periphery mixes with warmer core blood following induction; the temperature falls during the first 30 to 60 minutes up to 1.6°C. Even for short duration procedures, core temperature monitoring is useful. During the second phase, cooling slows, but because of the shift of shivering and vasoconstriction thresholds, the body is not able to compensate by increasing or conserving body heat. Depending on the ambient temperature, core temperature reaches a plateau phase after two to three hours which can be two to three degrees below normal temperature. [2] [4] [5] [15]



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Fig. 6: Mixing of core and peripheral blood following anaesthesia according to [4]



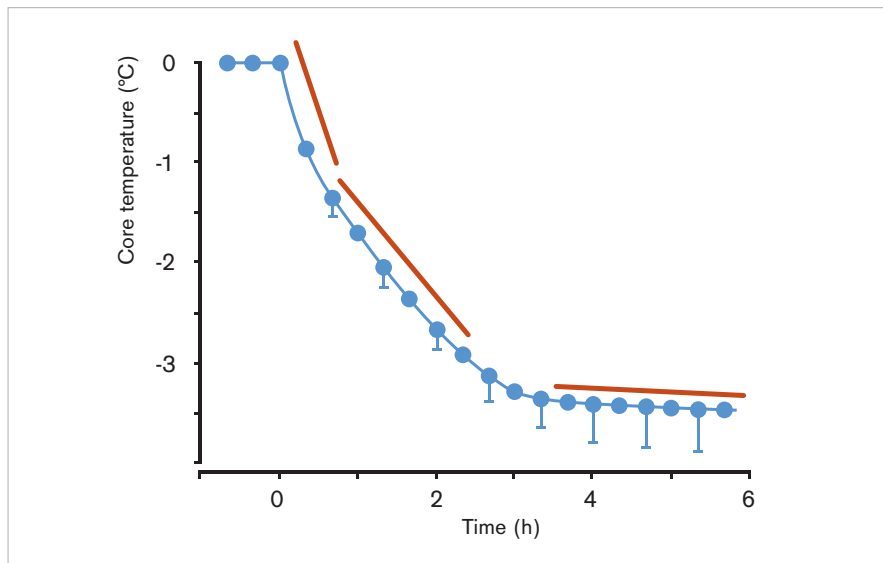


Fig. 7: Temperature changes following induction in non-warmed patients according to [4]

Near-spinal regional anaesthesia (epidural and spinal anaesthesia) also carries a risk of hypothermia. It is known to cause similar shifts in the shiver and vasoconstriction threshold. Mean skin temperature increases, however, and the patient feels warm, even though cooling is actually taking place. For this region, core temperature monitoring is essential. [3] [5] [15] [16] [17]

### 3.2.2 THERAPEUTIC (PROTECTIVE) HYPOTHERMIA

Therapeutic hypothermia, in which the patient is cooled under controlled conditions to 34 to 32°C has comparable sequelae to accidental hypothermia. The goal is to limit cerebral damage caused by apoptotic processes which increase the concentrations of free oxygen radicals, stimulating (excitatory) neurotransmitters and pro-inflammatory mediators. This form of therapeutic intervention has been included in the guidelines for patients who have suffered cardiac arrest as a result of ventricular fibrillation or pulseless ventricular tachycardia outside the hospital. Active cooling is also regularly used in cases of neonatal asphyxia. During some heart operations, the heart-lung machine is used to cool patients down between 14 and 20°C. [11] [18] [19] [20]

Following cardiac arrest, therapeutic hypothermia must be established rapidly following cardiac arrest in order to achieve effective neuroprotection. For every degree of cooling, metabolism is reduced by 10%. After 12 to 24 hours, slow, controlled re-warming is initiated. Several systems are available for therapeutic hypothermia which differ with respect to their efficiency, invasiveness and cost. For all systems, continuous core temperature monitoring is essential to ensure that mild hypothermia is maintained and to avoid undesirable side effects. Here, the typical side effects also seen in accidental hypothermia also arise, but the benefits are considered to outweigh the risks. [3] [11] [15] [17] [18] [19] [20]

### 3.3 CONSEQUENCES OF HYPOTHERMIA

Hypothermia has ramifications for the entire organism. Subjective symptoms include stress, uneasiness and the feeling of being cold. Shivering is a compensatory mechanism.

Other effects of hypothermia can include:

- prolonged effects of medication
- myocardial infarction, rhythm disturbances
- insulin resistance, hyperglycaemia – increased amylase activity, pancreatitis
- infections, wound infections, poor wound healing
- thrombocyte dysfunction, thrombocytopenia, increased intraoperative blood loss, intracerebral bleeding

[3] [4] [5] [6] [15] [16] [17] [21]

Often, hypothermia is recognised too late or not at all. Patient cooling goes unnoticed and the connection between cause and effect remains unclear. Rigorous temperature monitoring and management can help to avoid the negative effects of unrecognised hypothermia. The potential for financial savings is great, since every patient who suffers from perioperative undercooling requires additional treatment costing between 2,412 and 6,839 USD. Length of stay is increased by an average of 2.6 days. [2] [22] [23] [24] [25]

**COST EFFECTIVENESS BY MAINTAINING NORMOTHERMIA:  
ASSUMPTION: LOW COSTS PER PATIENT**

Parameter	Unit	Cost per unit [USD]	Savings [USD]
Erythrocytes [units]	1.05	112.00	117.60
Plasma [units]	1.10	65.00	71.50
Thrombocytes [units]	0.70	54.38	38.07
Length of stay [d]	7.67	200.00	1,534.00
ICU stay [h]	4.19	25.00	104.75
Infection [%]	12.12	4,500.00	545.40
Myocardial infarction [%]	1.77	3,823.33	67.67
Transfusion [%]	9.76	0.75	0.07
Mechan. ventilation [%]	6.42	250.00	16.05
Total savings	-	-	2,495.11
Post-mortem	-	-	2,412.57

**COST EFFECTIVENESS BY MAINTAINING NORMOTHERMIA:  
ASSUMPTION: HIGH COSTS PER PATIENT**

Parameter	Unit	Cost per unit [USD]	Savings [USD]
Erythrocytes [units]	1.05	218.50	229.43
Plasma [units]	1.10	69.91	76.90
Thrombocytes [units]	0.70	54.38	38.07
Length of stay [d]	7.67	600.00	4,602.00
ICU stay [h]	4.19	75.00	314.25
Infection [%]	12.12	14,000.00	1,696.80
Myocardial infarction [%]	1.77	5,097.60	90.23
Transfusion [%]	9.67	2.00	0.20
Mechan. ventilation [%]	6.42	400.00	25.68
Total savings	-	-	7,073.56
Post-mortem	-	-	6,839.55

Fig. 8: Potential savings by maintaining normothermia according to [22]

Age	Minor procedures [GBP]	Average procedures [GBP]	Major procedures [GBP]
20	219 (53–563)	611 (159–1,557)	770 (274–1,727)
50	1,476 (426–3,649)	1,868 (633–4,120)	2,027 (763–4,269)
70	1,576 (461–3,903)	1,968 (663–4,461)	2,127 (813–4,554)

Fig. 9: Potential savings by maintaining normothermia according to [13]

### 3.4 PREVENTION OF AND THERAPEUTIC INTERVENTION IN HYPOTHERMIA

Although the incidence of hypothermia in post-operative patients runs between 41 and 60%, temperature is measured in only one in four patients undergoing general anaesthesia in European hospitals. For regional anaesthesia, it is only one in six patients. Predictors for post-operative hypothermia include preoperative core temperature, extent of the procedure, intraoperative fluid turnover and the post-operative severity of condition as measured by the SAPS II score. [2] [26]

Pre-warming the patient is a method which has been successfully used to prevent the development of hypothermia in the surgical environment. With this method, the periphery is no longer able to cool the body's core as effectively following induction. It is recommended that pre-warming commence 30 to 60 minutes prior to induction. However, it has been shown that even a pre-warming period of 15 minutes can have a positive effect. [2] [9] [27] [28]

In clinical settings, it is possible to effectively prevent accidental hypothermia and thus minimise its effects. For very short procedures, improved patient insulation is sufficient to allow the body's own regulatory mechanisms to maintain normothermia. Heat dissipation can be reduced by increasing the ambient temperature. This technique is used in specialty areas, such as in incubators for neonatal therapy and on burn units. For each degree centigrade the temperature is increased, heat dissipation is reduced by 10%. This method is often considered impractical for regular operating rooms due to the detrimental effects on OR personnel.

When passive measures to maintain normothermia are insufficient, active thermal management can be used to warm the patient. A range of systems for a number of different specialties are available. These systems differ with respect to efficiency, invasiveness and cost. [2] [29] [30]

<b>Category</b>	<b>Method</b>	<b>Invasiveness</b>
passive, external	unwarmed blankets	low
	humidified breathing air	low
active, external	warm air blowers	low
	conductive warming	low
	warm water bath	(high)
	infrared light	low
	increasing ambient temperature	low
active, internal	warmed, humidified breathing air	intermediate
	warmed infusions	intermediate
	intravascular warming catheters	high
extracorporeal	extracorporeal haemodialysis/hemofiltration	high
	veno-venous warming	high
	arteriovenous warming	high
	extracorporeal membrane oxygenation	very high
	cardiopulmonary bypass	very high

Fig. 10: Categorisation of various warming methods according to [29]

## 4 Fever and hyperthermia

### 4.1 DEFINITION OF FEVER AND HYPERTHERMIA

The terms fever and hyperthermia both describe a state in which core temperature is increased above normal limits. While fever is considered to be a regulated physiological reaction, hyperthermia occurs when the body's thermoregulatory mechanisms are pushed beyond their limits. Depending on the definition, temperatures higher than 37.5°C are considered to be higher than normal.

### 4.2 CAUSES AND TYPES OF FEVER

Fever is a reaction of the human organism to both infectious and non-infectious challenges. In intensive care patients, infections are the most common cause of fever. These are usually in the form of pneumonia and sepsis. [31]

Aside from infections, non-infectious, inflammatory reactions can also lead to fever. These can be brought about by myocardial infarction, pulmonary embolism and tumours. It is rare that non-infectious reactions are sufficient to increase temperatures above 38.9°C. Exceptions include patients with fever reactions to pharmaceuticals or blood transfusions. Cerebral damage can cause fever of up to 40°C. Structured differential diagnostics are necessary in order to avoid inappropriate pharmaceutical therapy. [31]

**Non-infectious causes of fever**

Alcohol/drug withdrawal

Post-operative fever (48 h post-operative)

Post-transfusion fever

Drug fever

Stroke/intracerebral bleeding

Adrenal insufficiency

Myocardial infarction

Pancreatitis

Acalculous cholecystitis

Ischaemic bowel

Aspiration pneumonitis

Respiratory distress syndrome

Subarachnoid haemorrhage

Fat emboli

Transplant rejection

Deep venous thrombosis

Pulmonary emboli

Gout/pseudogout

Haematoma

Cirrhosis (without primary peritonitis)

GI bleed

Phlebitis/thrombophlebitis

IV contrast reaction

Neoplastic fevers

Decubitus ulcers

**Infectious causes of fever**

Ventilator associated pneumonia

Sinusitis

Catheter-related sepsis

Primary gram-negative septicaemia

C. difficile diarrhoea

Abdominal sepsis

Complicated wound infections

Fig. 11: Causes of fever on intensive care units according to [31]

The centre of the body's own temperature regulation system is located in the hypothalamus. During fever, the nominal value set point is increased. Characteristically, core temperature rises while peripheral temperature falls. With continuous thermal monitoring, this divergence can be used to distinguish fever from other causes of increased core temperature. In areas where thermoregulation is particularly sensitive, such as in neonatal intensive care, parallel monitoring of both the central and peripheral temperature has become routine. [6] [32] [33]

The increase in core temperature seen in fever is mediated by pyrogens. One subgroup includes exogenous pyrogens, which are made up of toxins and outer wall components of microorganisms. Endogenous pyrogens are produced by the body itself. These consist primarily of pyrogenic cytokines, which are produced by white blood cells (neutrophils, macrophages, lymphocytes) during an immune response. [32]

A regulatory mechanism ensures that body temperature does not rise beyond set limits during fever. Anti-inflammatory cytokines inhibit the synthesis of pyrogens. The blockade of cytokine receptors and the stimulation of temperature-sensitive neurons which leads to increased heat dissipation also limit the temperature increase. These antipyretic systems protect the body from the damaging consequences of uncontrolled fever. [32]

Both duration and level of the fever can offer hints as to its root cause. Acute fever lasting less than seven days is typical for infection, while subacute fever of less than two weeks can, among other things, stem from an intra-abdominal abscess. Chronic fever is associated with chronic infections such as HIV infections, but can also arise in connection with malignomas. High temperatures, above 38.9°C, point to the immune response to an infection. [32]

Both the course and the resolution of the fever reaction can aid in the diagnosis. Characteristic fever curves can provide clues as to the cause. [32] [34] [35]



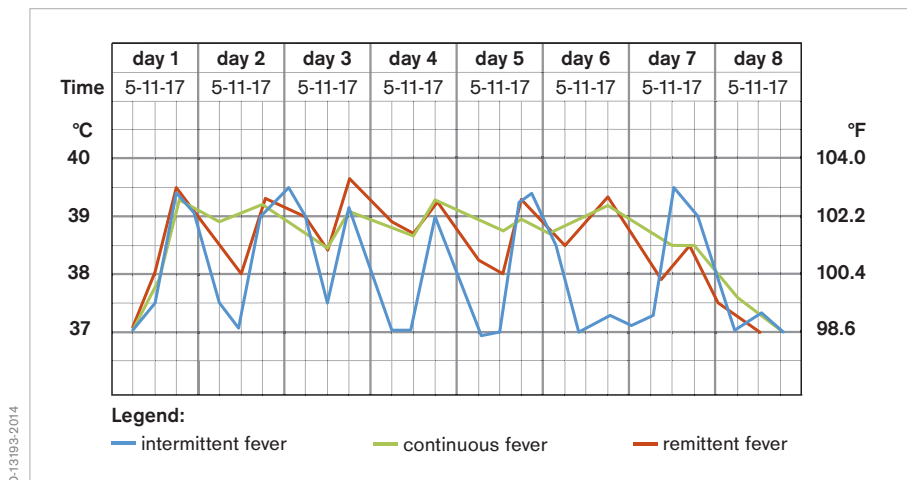


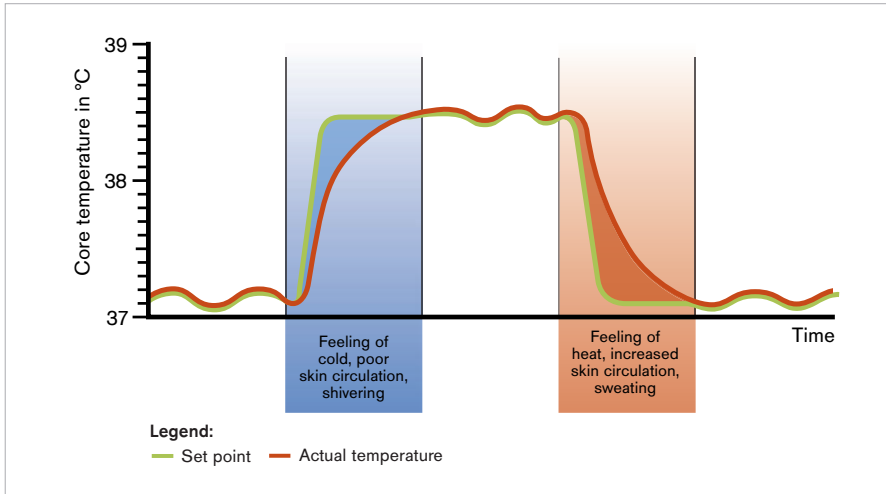
Fig. 12 The course of various types of fever according to [36]

### 4.3 THE CONSEQUENCES OF FEVER

Fever is a core function within the unspecific immune response. An increase in temperature activates T-lymphocytes, neutrophils and macrophages and stimulates the production of antibodies and cytokines, thereby modulating the immune system. Simultaneously, the growth of many microbial pathogens which thrive at normal temperatures is inhibited. Very high temperatures, above  $41^{\circ}\text{C}$ , can lead to the derangement of the coagulation system and disturb enzyme function. Hallucinations and confusion can also occur. In addition, hyperthermia causes an increase in cardiac output, increasing oxygen consumption and fluid losses. [31] [35]

### 4.4 THERAPEUTIC INTERVENTION IN FEVER

Fever is not just a symptom, but is rather part of an important defence system. For this reason, the central focus should be the treatment of its cause and not simply the reduction of the temperature. Furthermore, the course of a fever curve can provide valuable information as to its pathogenesis and the success of therapeutic countermeasures. The increase in the set point within the hypothalamus causes the same peripheral vasoconstriction observed in cold environments. Additional external cooling can lead to hypermetabolism and continued fever. Physical cooling is therefore often contraindicated in patients with fever (not hyperthermia). [31] [32]



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Fig. 13: Fever curve

#### 4.5 CAUSES AND TYPES OF HYPERTHERMIA

Hyperthermia differs from fever in that it is not a condition which is subject to the body's regulatory mechanisms. If an organism is heated externally or produces more warmth through activity than it can effectively radiate to the environment, both peripheral and core temperatures will rise. Pyrogens are not involved in hyperthermia, which is why antipyretic medication is ineffective.

##### 4.5.1 THERAPEUTIC HYPERTHERMIA

Therapeutic overheating of either specific regions of the body or the entire organism is used primarily in cancer therapy. Because of their limited blood supply, tumour cells cannot dissipate heat as effectively as healthy cells. Therapeutic hyperthermia causes localised thermal build-up within the cancerous tissue which in turn leads to oxygen and nutrient starvation. Hyperthermia activates the body's immune response by increasing the presentation of tumour antigens on the surface of the tumour cells. This in turn increases the likelihood of their detection. Beyond oncology, therapeutic hyperthermia is used to treat rheumatoid arthritis, arthrosis and migraine headache. [37] [38] [39] [40] [41]

#### 4.5.2 MALIGNANT HYPERTHERMIA

Malignant hyperthermia is a very rare, life-threatening condition caused by a severe disturbance of skeletal muscle metabolism brought about by anesthetic agents. Early signs include high carbon dioxide concentrations (hypercapnia), increased heart rate (tachycardia), muscle stiffness (rigor) acid build-up (acidosis) and oxygen deprivation (hypoxia). This is followed by an increase in temperature (hyperthermia). Rhythm disturbances, a fall in blood pressure (hypotension) muscle cell breakdown (rhabdomyolysis) and potassium release (hyperkalemia) also occur. Malignant hyperthermia is an anaesthesia emergency and requires the immediate interruption of the administration of anesthetic agents. The muscle relaxant dantrolen, which must be readily available at every anaesthesia workstation, offers effective causal therapy. [42]

#### 4.6 CONSEQUENCES OF HYPERTHERMIA

Sweating leads to fluid loss. Another negative consequence is the increase in cardiac output caused by increase in body temperature. Energy and oxygen demand increases for every degree centigrade by 10% [31] [35]

## 5 Measurement locations and methods

### 5.1 CURRENT TECHNOLOGY

As far back as ancient times, the connection between warmth and the expansion of materials had been recognised. One of the earliest instruments to measure temperature was the thermoscope (Fig. 14), a glass flask which, when partially submerged in water, rose and sank depending upon the temperature. Later, in place of air, the expansion of alcohol, mercury and gallium were used to measure temperature. Beginning with the first temperature scales, developed in 1701 by Christensen Rømer, Daniel Gabriel Fahrenheit in 1724 and Anders Celsius in 1742 defined reference temperatures which were to become the basis for modern thermometry.

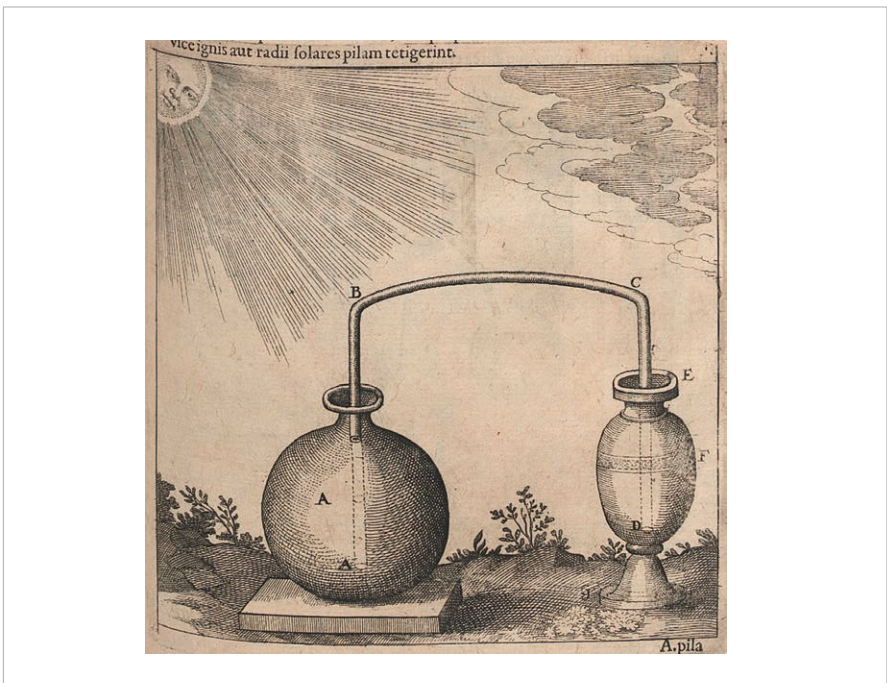


Fig. 14: Thermoscope

The first comprehensive study on core temperature was conducted in 1868 by Carl Reinhold August Wunderlich ("The behaviour of self-warmth in disease", fig. 15). This pioneer in the fields of physiology and medicine measured the body temperature of a large number of patients and laid the groundwork for systematic observation. Wunderlich described in detail the difficulties involved with measuring core temperature which are still relevant to this day.

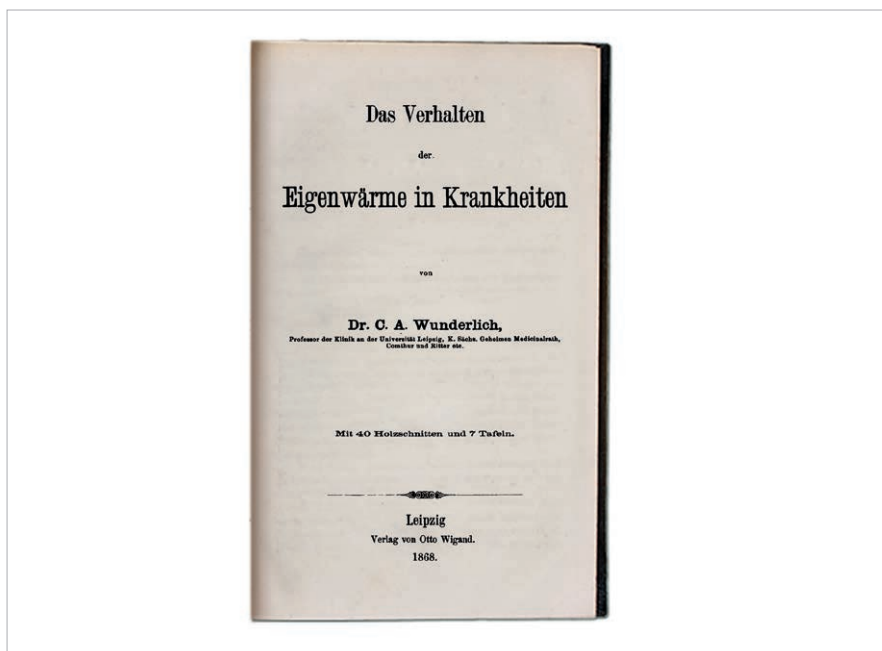


Fig. 15: The behaviour of self-warmth in disease

For many years, determination of body temperature using a mercury thermometer was standard practice. This method has a great number of disadvantages. During the early years in particular, very large instruments which were difficult to read were used. Furthermore, the method is slow and carries the risk of the release of harmful mercury. Although many mercury thermometers are still in use today around the world, the technology of expansion thermometers is increasingly giving way to electronic and other forms of thermometry.

Electronic measurement techniques often used with patients today operate with thermistors and thermal elements which offer very good (laboratory) precision of  $\pm 0.1^{\circ}\text{C}$ . Liquid crystal and infrared sensor technologies are also used in modern thermometers. Thermistor-based and thermal-element-based electronic thermometers consist of casing with good thermal transmission properties, within which the sensor is located. These casings can be adapted and miniaturised for use on the skin, but also in body cavities and even within tissues and blood vessels.

Temperature measurement methods based on detecting radiant heat have the advantage that the measurement can be performed remotely. The use of infrared technology to measure the temperature of the eardrum or the temporal artery to extrapolate core temperature is widespread.

Lastly, temperature can be measured by sensing thermal flux. Active thermal flux thermometers, known as zero-heat-flux thermometers, and their passive counterparts are generally based on thermistor technology.

All electronic methods harbour the inherent disadvantage that their output, a digital number, can suggest a false level of precision. In addition, almost no core temperature thermometer provides information on possible measurement errors, dislocation or artefacts.

Methods for measurement of core temperature can be categorised according to their invasiveness:

- All temperature measurement methods which involve measurement of the sink's surface are non-invasive.
- Methods in which a temperature probe is inserted into a natural body orifice without undue patient discomfort (mouth, ear, rectum) are considered to be minimally invasive.

The most precise measurement results are obtained using invasive methods. These, however, are only used in the intensive care setting. For patients who are at risk of brain tissue damage, for example following head injury, brain haemorrhage or are undergoing surgical procedures which can adversely affect cerebral circulation, intracerebral temperature monitoring in combination with intracerebral tissue oximetry may be indicated. Core temperature measured in the vicinity of the heart is relevant for many cardiac surgery patients. Both of these methods are, however, maximally invasive: intracerebral temperature

can only be measured directly within the brain by means of trepanation. To measure core temperature near the heart, venepuncture of large-calibre vessels is necessary for insertion of a Swan-Ganz floating catheter (pulmonary catheter). Although they theoretically represent gold standards, these methods are only feasible if the corresponding indications for cranial trepanation or pulmonary artery catheterisation are given. In and of themselves, they are not suitable for measuring temperatures for comparative studies.

In practice, the optimal choice of temperature measurement location is dependent upon numerous factors:

- The state of consciousness of the patient (awake, sedated or under anaesthesia) determines the tolerable invasiveness.
- The probability that rapid changes in temperature can occur and the need for rapid, single measurements determine the choice of quicker or slower measurement methods.
- The need for documentation of temperatures over extended periods determines the need for either discrete or continuous measurement methods.
- Simple screening for fever or hypothermia is less difficult than obtaining the most accurate measurement possible.

## 5.2 NON-INVASIVE METHODS FOR CORE TEMPERATURE MEASUREMENT

### 5.2.1 AXILLARY SKIN TEMPERATURE MEASUREMENT

Axillary temperature measurement is still one of the most common methods used the world over. This is true both in the home and, in spite of known accuracy issues, the hospital settings. Axillary temperature is measured by placing a thermometer in the armpit near the axillary artery and holding it in place by pressing the upper arm against the chest wall. Axillary temperature is usually one to two degrees centigrade lower than the actual core temperature.

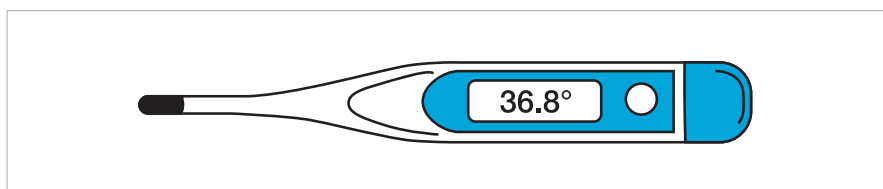


Fig. 16: Digital fever thermometer

Additional measurement errors can occur by shortening the duration of the measurement or through dislocation of the thermometer. Because of the long measurement time, the propensity for errors and the inherent inaccuracy of this method, it can no longer be recommended for clinical use. [44] [45] [46] [47] [48] [49]

## 5.2.2 FOREHEAD SKIN TEMPERATURE MEASUREMENT

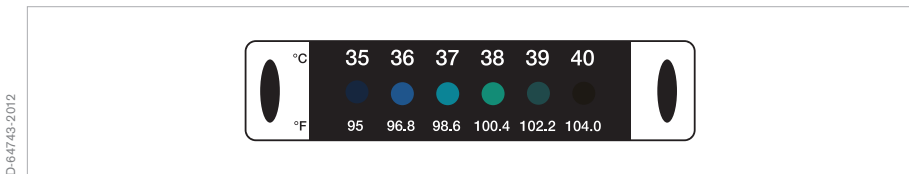


Fig. 17: Liquid crystal thermometer

The measurement of body temperature from the surface skin of the forehead is also a common method. The ‘sensor’ most frequently used is the human hand, which can differentiate between fever and normothermia with a level of sensitivity comparable to that of other imprecise yet technologically more advanced measurement methods. [50] [51] [52]

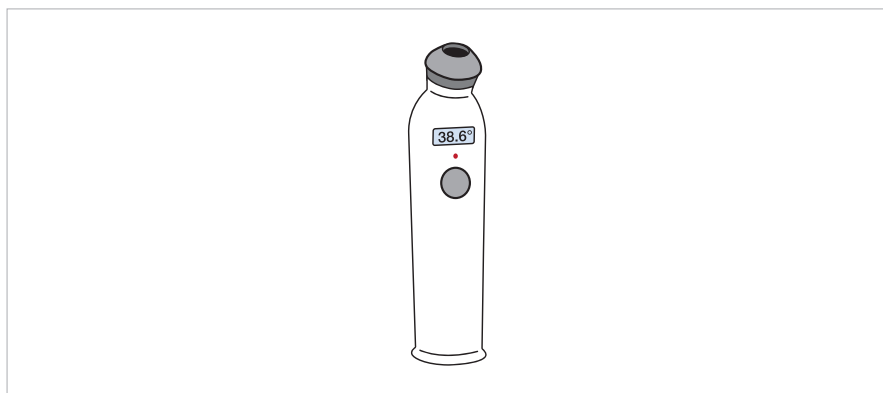
Forehead skin temperature is often measured using liquid crystal thermometers. Thermochromic liquid crystals change colour as a function of their temperature. Liquid crystal thermometers feature either a course temperature scale or simply indicate the presence or absence of fever. For clinical purposes, liquid crystal thermometers are too imprecise.

Direct skin temperature measurements are possible using thermistor or thermal element technology. Approximately two degrees must be added to the measured skin temperature in order to estimate core temperature. [57]



The main issue with forehead temperature measurements is that they are not representative, as is the case for all other skin surface measurements, of core temperature. Skin temperature is very sensitive to a number of external (sun exposure, cold air) and internal (perspiration, vasoconstriction) factors. [58]

### 5.2.3 TEMPORAL ARTERY THERMOMETER



D-64739-2012

Fig. 18: Temporal artery thermometer

Temporal artery thermometers also measure temperature on the forehead, but in contrast do so directly over the temporal artery. These thermometers are moved across the forehead while measurements are carried out; the highest temperature registered is usually directly over the temporal artery. Temporal artery thermometry has issues and problems similar to those associated with forehead skin measurements: poor correlation to core temperature, dependence on ambient factors and measurement errors due to skin cooling through perspiration. Temporal artery thermometers are not suited for clinical situations which call for high accuracy and reproducibility. Systems currently available for use do not allow for continuous measurement. [59] [60] [61] [62] [63]

### 5.3 MINIMALLY INVASIVE METHODS FOR CORE TEMPERATURE MEASUREMENT

#### 5.3.1 ORAL MEASUREMENT

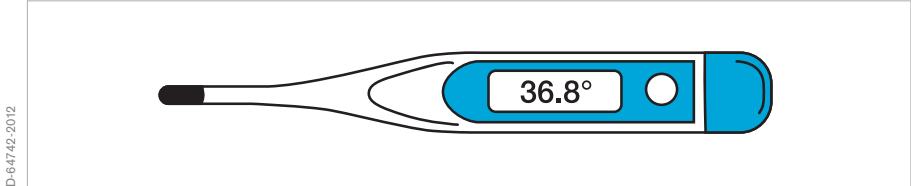


Fig. 19: Digital fever thermometer

A commonly used measurement location for body temperature is the oral cavity. Typically, the patient is instructed to hold the thermometer under the tongue. Depending on patient compliance, a more or less accurate approximation of core temperature is possible. Changes in oral temperature brought about by foodstuffs, mucosal inflammation or circulating air can be problematic. Here again, continuous temperature measurements are not possible. [64] [65]

#### 5.3.2 CORE TEMPERATURE MEASUREMENT VIA THE EARDRUM

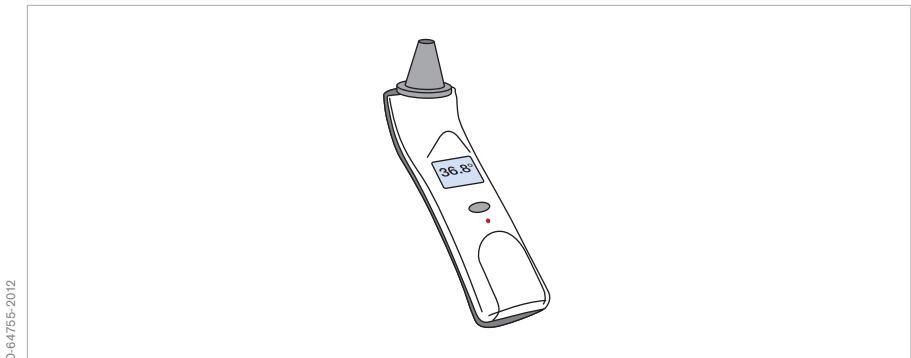
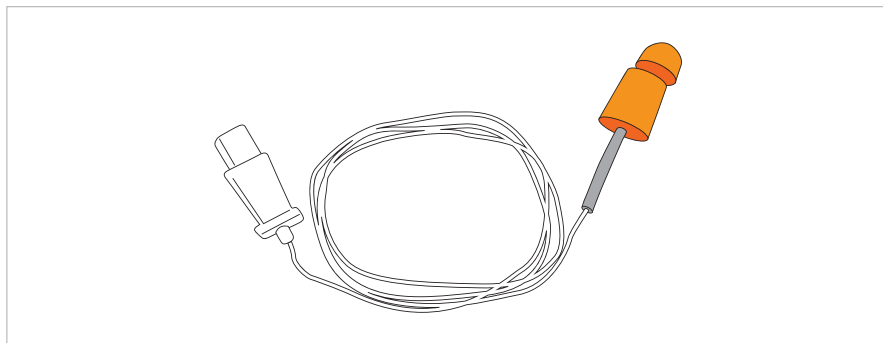


Fig. 20: Infrared thermometer

One of the most widespread temperature measurement methods is the tympanic temperature measurement using an infrared sensor. However, this principle is subject to error and inaccuracy. The measurement is performed by inserting the sensor into the ear canal of the patient. Ideally, the sensor then measures the

temperature of the eardrum, which is representative of core temperature. Often, however, this is not the case; the thermometer is not inserted adequately, or, for safety reasons, is manufactured in such a way so as to prohibit insertion far enough down the ear canal. The ear canal generally contains cerumen, which can disturb the measurement. Thus, the IR measurement often delivers the temperature of the external ear canal or cerumen, rather than core temperature. [66] [67] [68] [69] [70] [71] [72] [73]

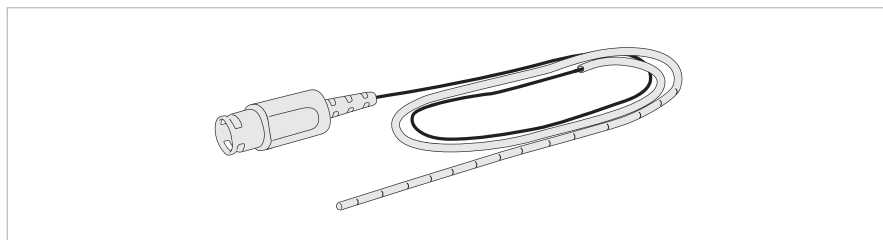


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Fig. 21: Temperature probe for direct contact measurement of eardrum

The direct temperature measurement on the eardrum is possible by using specialised cotton swab probes which are brought into direct contact with the eardrum. It delivers accuracy similar to that of the oesophageal measurement, but is relatively difficult to perform. For the patient, it is hardly tolerable, as contact with the eardrum causes significant pain. The method also harbours the potential risk of tympanic perforation. [74] [75]

### 5.3.3 RECTAL MEASUREMENT



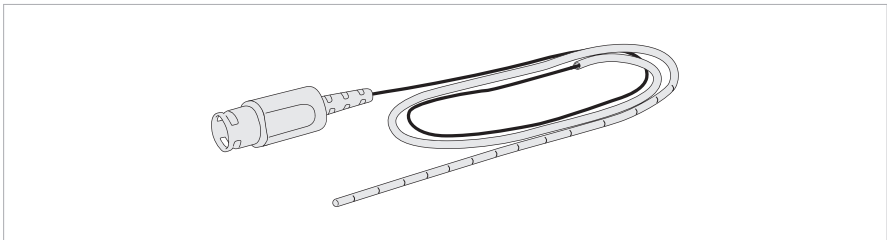
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Fig. 22: Temperature sensor

For the rectal measurement, a temperature catheter is inserted through the anus and advanced several centimetres into the rectum. A significant disadvantage of this method is the high amount of latency involved, depending on the contents of the rectal ampulla. A full ampulla can delay accurate measurement of core temperature for up to an hour. Securing the rectal thermometer for use over longer periods also often presents practical difficulties. Rarely, intestinal perforation can occur, particularly if the probe is advanced too deeply. In spite of its disadvantages, it should be considered to be the preferred minimally invasive method. It is, however, less accurate than more invasive temperature measurement methods such as the oesophageal or bladder methods. [48] [76] [77] [78]

## 5.4 INVASIVE METHODS FOR CORE TEMPERATURE MEASUREMENT

### 5.4.1 NASOPHARYNX

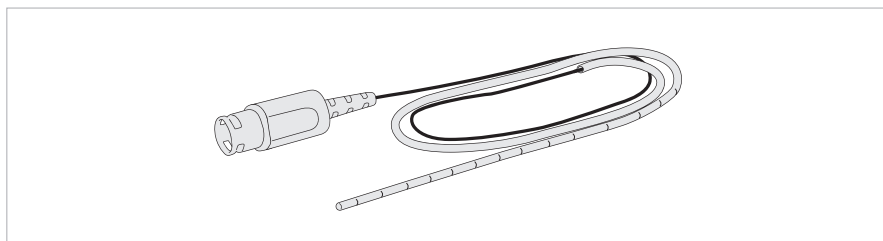


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Fig. 23: Temperature probe

As a rule, temperature measurement via the nasopharynx is only possible in the anaesthetised patient. The sensor is inserted through the nose and placed above the hard palate in the nasal cavity. In conscious patients, the probe causes significant discomfort. Additionally, the air stream in the nasopharynx caused by ventilation can heavily skew the measurement. A possible complication of the nasopharyngeal method is epistaxis. Under the proper conditions, however, the method is relatively accurate and representative for actual core temperature. [79]

### 5.4.2 OESOPHAGUS

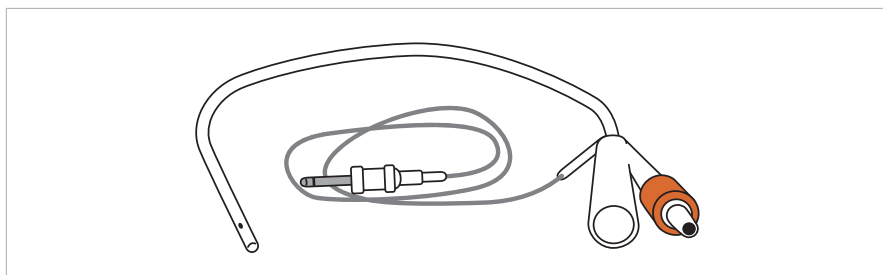


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Fig. 24: Temperature probe

For the oesophageal measurement, the probe is inserted through the mouth or nose and advanced down the oesophagus to the level of the heart. Insertion through the nose can cause epistaxis; oesophageal varices can bleed. As with the nasopharyngeal method, the oesophageal temperature measurement method causes discomfort in conscious patients. Due to its high level of accuracy and low propensity for dislocation, it is often used in anaesthetised patients. The oesophageal measurement is thus often used as an alternative method to more invasive methods (e.g. pulmonary arterial catheter) in comparative studies. [48] [80] [81]

### 5.4.3 BLADDER



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Fig. 25: Bladder catheter with temperature measurement probe

For the bladder temperature measurement, a bladder catheter is inserted which features a temperature probe at its distal tip. The method is particularly useful in patients requiring a bladder catheter during the course of their treatment and

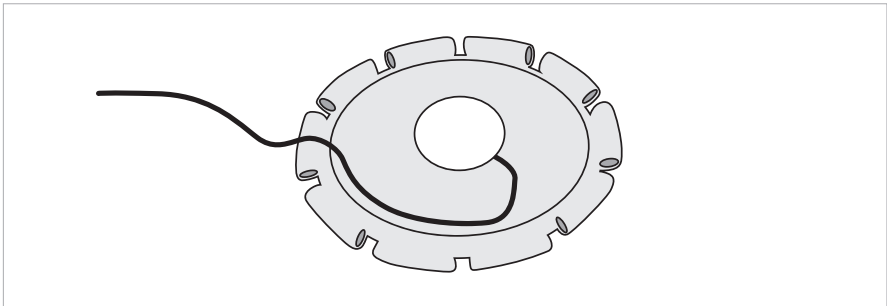
harbours no additional risk in comparison with regular bladder catheters. Advantages include a low likelihood of dislocation and a relatively high level of accuracy. [48] [82] [83] It is used in comparative studies in conscious patients requiring bladder catheterisation as an alternative to more invasive methods. Several studies do cite the fact that the temperature of the bladder can depend on urine output. [84] [85]

## 5.5 NEW TECHNOLOGIES

### 5.5.1 ZERO-HEAT-FLUX TECHNOLOGY

Zero-heat-flux technology is based on the thermal isolation of a portion of the skin and an active heating element. Thermal equilibrium is established between the skin and the heating element, which allows calculation of core temperature. The system requires an active heating element and therefore a power source. For the patient, wearing the sensor for prolonged periods is uncomfortable due to the heat generated. For obvious reasons, it cannot be used in combination with active warming systems. Zero-heat-flux sensors are commercially available, although their use is not widespread in spite of their high level of accuracy. [86] [87]

### 5.5.2 HEAT FLUX/DOPPLER SENSOR TECHNOLOGY



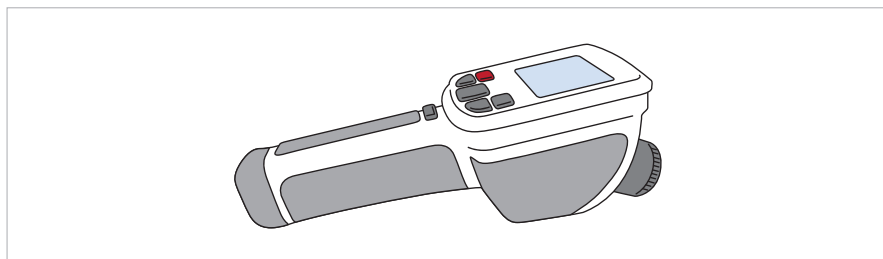
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Fig. 26: Heat flux/Doppler sensor technology

Heat flux or Doppler sensor technology eliminates the need for an active heating element. Here, the heat flux of an isolated area of skin is measured with the help of two temperature sensors and a defined thermal isolator, allowing the determination of body core temperature. This principle makes their use comfortable and practical in combination with active warming systems. [88] [89]

Both heat flux methods are characteristically minimally invasive and highly accurate. They are not useful for rapid screening, since a latency of several minutes is inherent before the thermal equilibrium is achieved and accurate measurements are possible. Following equilibration, rapid reporting of changes in core temperature is possible.

### 5.5.3 THERMOGRAPHY



D-64741-2012

Fig. 27: Infrared camera

Thermography involves the visualisation of a region of the body using an infrared camera. This makes it possible to register the temperature distribution on the patient's skin surface. The method lacks sufficient accuracy to measure core temperature, but has several specialised applications such as the observation of temperature in grafts, the recognition of vasoconstriction and centralisation, measurement of heat loss during operations and mass temperature screening. [90]

<b>Location</b>	<b>Accuracy</b>	<b>Latency</b>	<b>Invasiveness</b>	<b>Comfort</b>	<b>Aspects</b>
Pulmonary artery	gold standard	low	high	low	infection, complications from venepuncture*
Oesophagus	good	low	moderate	low	oesophageal perforation (rare), uncomfortable for conscious patients, influenced by breathing
Bladder	good	low	high	low	infection**, accuracy dependent on urine output
Rectum	moderate	high	moderate	low	local irritation, rectal perforation
Nasopharynx	good	low	moderate	low	local irritation/laceration, dislocation, epistaxis
Gastrointestinal	good	moderate/high	low	high	no standard measurement position
Eardrum, with contact	good	low	moderate	low	local irritation, perforation of the eardrum, dislocation
Eardrum, remote (IR)	low	low	low	high	accuracy
Oral	moderate	low	low	moderate	accuracy
Axillary	low	high	low	high	accuracy
Forehead	good	high	low	high	long starting time
Medial palpebral angle	low	moderate	low	high	unreliable

\* The pulmonary arterial catheter is used almost exclusively for haemodynamic monitoring. In this case the temperature measurement does not increase the invasiveness of the risk of complications.

\*\* The bladder catheter is used for urinary drainage. In this case the temperature measurement does not increase the invasiveness of the risk of complications. Insertion for temperature measurement purposes alone is not indicated.

Fig. 28: Comparison of various temperature measurement methods [6]



## 5.6 EXPERIMENTAL TECHNOLOGIES

### 5.6.1 ULTRASONIC TEMPERATURE MEASUREMENT

The speed with which ultrasound penetrates tissue is, among other things, temperature-dependent. Tissue temperature can be calculated using the reflections of ultrasonic waves. [91]

### 5.6.2 MAGNETIC RESONANCE TEMPERATURE MEASUREMENT

Similarly, various parameters in magnetic resonance tomography are affected by temperature. In principle, this allows measurements with an accuracy of up to 0.2–0.3°C. A significant advantage of this application would be to monitor the temperature during prolonged imaging sessions in order to ensure that the radio waves used do not drive tissue temperatures to dangerous levels. [92] [93]

### 5.6.3 SIMULATION OF CORE TEMPERATURE

Changes in core temperature can be anticipated through simulation. This can be used for decision support when it comes to choosing a warming method (e.g. active warming versus passive warming during an operation). For such simulations, patient and environmental parameters as well as time estimations are used by modelling software to simulate the probable course of a core temperature curve. In simple conditions, the changes in core temperature over time can be estimated fairly accurately. [94] [95] [96]

### 5.6.4 BRAIN TEMPERATURE TUNNEL

The theory behind the brain temperature tunnel assumes that a direct temperature tunnel exists (above the superior ophthalmic vein) which leaves the brain through the medial canthus and allows direct measurement of brain temperature. There is considerable scientific dispute as to whether such a tunnel between the brain and the medial canthus actually exists. In the USA, the first brain tunnel measurement devices have already reached the market. [97]

## 6 Non-invasive measurement of core temperature using Doppler sonography technology

In the anesthesiological and intensive care settings, core temperature measurement is routinely used during vital parameter monitoring. If exact, continuous measurement is indicated, invasive methods are used (rectum, oesophagus, bladder). These techniques deliver reliable results, but are somewhat arduous and uncomfortable for patients. For these reasons, continuous monitoring is often not used, although it is medically indicated. Non-invasive measurement techniques such as axillary, oral or ear temperature are much easier to use and are less invasive but are also inaccurate and not suited for continuous measurement. Their use in the clinical setting is therefore limited.

A new method to measure core temperature continuously and non-invasively is now possible through Doppler sensor technology.

The Doppler sensor system measures core temperature from the skin surface. It consists of two temperature probes which are separated by an isolating layer. It is attached to the forehead.

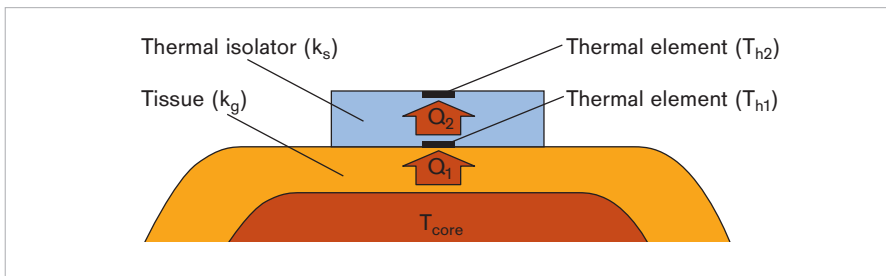


Fig. 29: Schematic of the Doppler sensor

While one sensor registers the near-surface skin temperature ( $T_{h1}$ ), the other ( $T_{h2}$ ) measures heat flux ( $Q_2$ ) to the surrounding tissue. This allows calculation of near-core body temperature.

Calculations are performed using the following equation:

$$T_{\text{core}} = T_{\text{h1}} + \frac{k_s}{k_g}(T_{\text{h1}} - T_{\text{h2}})$$

$k_s$  describes the thermal conductivity coefficient of the sensor,

$k_g$  the thermal conductivity coefficient of the tissue.

$T_{\text{h1}}$  and  $T_{\text{h2}}$  are the temperatures of both sensors;

$T_{\text{core}}$  corresponds to the intracranial core temperature.

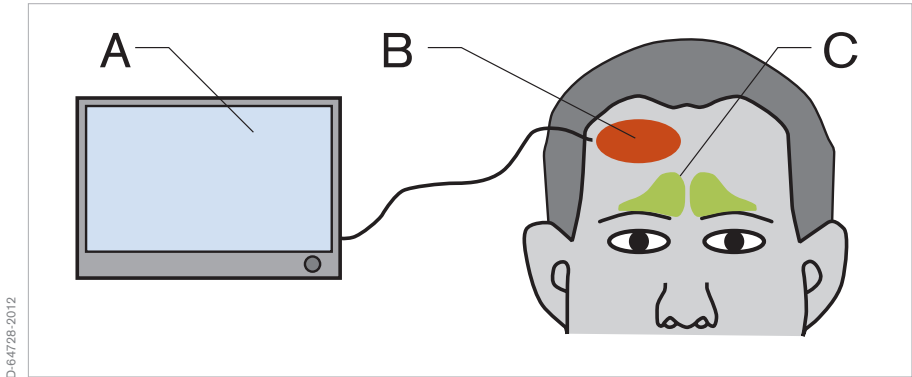
$Q_1$  corresponds to the heat flux between the core and the skin,

$Q_2$  the heat flux between both sensors.

Assuming that the heat flux  $Q_2$  through the sensor corresponds to the heat flux  $Q_1$  through the skin, core temperature can be calculated by measuring the temperatures of both sensors.

The system delivers valid, continuous values after the sensor is attached to the skin and thermal equilibrium is reached.

A clinical study has shown that the accuracy of the Doppler sensor method is comparable to oesophageal or bladder measurement methods. The technical accuracy (laboratory accuracy) of the Doppler sensor is labelled at  $\pm 0.1^\circ\text{C}$  on the sensor components. Clinical accuracy reaches that of oesophageal and bladder measurements at core temperatures between  $35$  and  $38^\circ\text{C}$  and ambient temperatures between  $15$  and  $40^\circ\text{C}$  with a standard deviation of  $\pm 0.3^\circ\text{C}$  and a bias of close to  $0^\circ\text{C}$ . 90% of measurements deviate less than  $0.5^\circ\text{C}$  from the reference measurement. In another study, it was demonstrated that no differences were observed in the accuracy of the method when used in either regional or general anaesthesia. [89] [98]



D-64728-2012

Fig. 30: The Doppler sensor in practice

- A: Patient monitor
- B: Double sensor
- C: Sinus cavities

The principle of heat flux measurement makes the Doppler sensor system independent of ambient temperature. Its reliable function has also been demonstrated when used together with warm air blankets and in operating rooms under laminar air flow conditions.

## 7 Summary

The body contains a number of temperature compartments, each of them with its own significance. For clinical diagnoses and with respect to legal limits, core temperature is decisive. Since core temperature varies and undulates, profound knowledge of this variability is necessary in order to interpret its meaning. Although temperature is an important vital parameter, it is often not given the attention it deserves in a day-to-day clinical setting. This may be due to the fact that it appears relatively banal, subject to only slow changes (at least in adults). However, a deviation of less than  $0.5^{\circ}\text{C}$  from normal values activates the body's thermoregulatory mechanisms. It is therefore necessary to control core temperature within narrow limits, as temperatures beyond these normothermic limits can have potentially serious ramifications.

One problem which is often underestimated is that of accidental perioperative hypothermia, the effects of which on clinical outcome and, with that, on the patient and the hospital itself are not always recognised in a timely manner. The connection between cause and effect is much more difficult to make out.

Today, a large number of methods exist to measure core temperature. As a rule, the more invasive methods tend to deliver better accuracy. The gold standards still involve measurements in the pulmonary artery or the cerebrum, but are usually substituted for bladder or oesophageal measurement methods due to their less invasive nature. In order to obtain correct measurement results, the measurement method and the location, as well as the interpretation of the measured value, are important factors. Digital thermometers, currently in widespread use, are too inaccurate for clinical use, even though the digital display suggests greater precision. An ideal ratio of low invasiveness to high accuracy combined with ease of use is now achievable with the use of Doppler sensor technology, which is based on the principle of heat flux measurement.

In many countries, thermal management has been integrated into the corresponding OR and intensive care recommendations and guidelines, which all advocate continuous and exact temperature measurement. In order to improve future therapeutic outcome, reduce costs and to optimise comfort for both the patient and the user, it is necessary to increase awareness on the subject of thermal management and to consequently utilise available technologies for measuring core temperature as a routine practice.

## 8 Frequently asked questions

### **WHAT LEVEL OF ACCURACY SHOULD A THERMOMETER HAVE IN THE CLINICAL SETTING?**

The term accuracy is often used in layman's terms to describe two different things which both provide information on the quality of the measurement device. Accuracy can be thought of as the deviation between a measured value and the true value. Precision, or reproducibility, on the other hand, is how well several measurements of the same object agree with one another. A good measurement should be accurate and precise. Variance provides indispensable information on the quality of the measurement, as it describes how many of the measured values are actually within a defined region. With a variance of one standard deviation, that is only around 68% of all values, whereas with two standard deviations, 95% of the values are included. With respect to core temperature, a good thermometer should be accurate to  $0.5^{\circ}\text{C}$  at two standard deviations when compared to the gold standard. This is the threshold at which thermoregulatory mechanisms are activated. This is why this value is used as a limit in numerous studies.

### **CAN A NON-INVASIVE THERMOMETER BE AS ACCURATE AS AN INVASIVE THERMOMETER?**

In order to answer this question, it is first necessary to differentiate between technical and clinical accuracy. Often the accuracy level claimed by the manufacturer is understood to be technical accuracy. Here, measurements are performed using a normed water bath. More important for practical purposes is the clinical accuracy, and this is often lower since the clinical setting allows a number of ambient influences on the measurement. For example, an ear thermometer often does not take the temperature of the eardrum, but rather that of the ear canal, resulting in a measurement error with respect to actual core temperature. An additional factor is the question as to whether the method used or the location chosen allows the inference of core temperature at all. If the chance for user error is low and the measurement location is suitable, a non-invasive thermometer can be used to determine core temperature with a high degree of accuracy. For the Doppler sensor method, for example, it has been demonstrated that it can replace the bladder or oesophageal measurement method for the determination of core temperature in the clinical setting.

## **WHY IS IT SO DIFFICULT TO COMPARE THE GOLD STANDARD TO THE DOPPLER SENSOR IN CLINICAL STUDIES?**

The gold standard for core temperature measurements is the pulmonary artery or the cerebrum. These methods are naturally highly invasive. Because of the large body of knowledge which has already been gathered on the temperature parameter, it is not considered ethical to use it as a reference method. The same is true for research at the extreme limits of core temperature. Instead, the less invasive methods of bladder and oesophageal measurement are used. Because these substitute methods harbour a certain amount of uncertainty, the results of the Doppler sensor method can also be influenced in comparative measurements.



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### REGION EUROPE CENTRAL AND EUROPE NORTH

Dräger Medical GmbH  
Moislinger Allee 53–55  
23558 Lübeck, Germany  
Tel +49 451 882 0  
Fax +49 451 882 2080  
[info@draeger.com](mailto:info@draeger.com)

### REGION EUROPE SOUTH

Dräger Médical S.A.S.  
Parc de Haute Technologie d'Antony 2  
25, rue Georges Besse  
92182 Antony Cedex, France  
Tel +33 1 46 11 56 00  
Fax +33 1 40 96 97 20  
[dlmfr-contact@draeger.com](mailto:dlmfr-contact@draeger.com)

### REGION MIDDLE EAST, AFRICA

Dräger Medical GmbH  
Branch Office  
P.O. Box 505108  
Dubai, United Arab Emirates  
Tel +971 4 4294 600  
Fax +971 4 4294 699  
[contactuae@draeger.com](mailto:contactuae@draeger.com)

### REGION ASIA / PACIFIC

Dräger Medical  
South East Asia Pte Ltd.  
25 International Business Park  
#04-27/29 German Centre  
Singapore 609916, Singapore  
Tel +65 6572 4388  
Fax +65 6572 4399  
[asia.pacific@draeger.com](mailto:asia.pacific@draeger.com)

### REGION CENTRAL AND SOUTH AMERICA

Dräger Panama  
Comercial S. de R.L.  
Complejo Business Park,  
V tower, 10th floor  
Panama City  
Tel +507 377 9100  
Fax +507 377 9130  
[contactcsa@draeger.com](mailto:contactcsa@draeger.com)

### CANADA

Dräger Medical Canada Inc.  
2425 Skymark Avenue, Unit 1  
Mississauga, Ontario, L4W 4Y6  
Tel +1 905 212 6600  
Toll-free +1 866 343 2273  
Fax +1 905 763 1890  
[Canada.support@draeger.com](mailto:Canada.support@draeger.com)