Perioperative Temperature Monitoring

Daniel I. Sessler, M.D.

Body temperature is among the classical vital signs, and for good reason, since thermal perturbations both cause and indicate disease. Aside from infectious fever, hypothermia during surgery is the most common temperature disturbance. Temperature monitoring and thermal management are therefore key responsibilities for anesthesia professionals. Detailed reviews of thermoregulation,[1] heat balance,[2] and consequences and treatment of hypothermia[3] have been published in this journal. There are dozens of clinical indications for temperature measurement, but this review will focus on those most relevant to anesthesia.

Body Temperature

Normal human core body averages about 37°C. However, there is a superimposed circadian rhythm with roughly a 1°C range. Normal core body temperature thus varies from ≈36.5°C (usually about 3:00 AM) to ≈37.5°C (usually about 3:00 PM).[4] In premenopausal women, there are also superimposed changes in temperature with the menstrual cycle, with core temperature being about 0.5°C greater during the luteal phase.

Body temperature is not homogeneous.[5] The thermal core consists of highly perfused central tissues, mostly the trunk and head, that have a relatively homogeneous and high temperature.[6] But even the core is not uniform; for example, liver temperature is about a degree Celsius greater than most other core tissues. Core temperature is therefore the average temperature of core tissues, perhaps best represented by pulmonary artery blood temperature. Core temperature does not fully characterize body temperature, but it is the single most important temperature because it is the dominant input to autonomic thermoregulatory control[7] and is probably the major determinant of temperature-related complications.

In hospital environments, the arms and legs are usually 2 to 4°C cooler than the core, and the skin surface is yet cooler. Skin temperature varies considerably as a function of ambient temperature, air speed, and peripheral perfusion.[8,9] A downward thermal gradient from the core to peripheral tissues to the skin surface is necessary so that heat generated in the core can flow to the skin and be dissipated to the environment.

Muscle or skin surface temperatures can be used to evaluate vasomotion.[9] Cool nerves and muscles respond poorly to ulnar nerve stimulation. Hand skin temperature is therefore usually monitored during neuromuscular block studies.[10] Skin temperature can also help evaluate sympathetic blocks, and to assess regional inflammation and perfusion. Muscle temperatures are also used to determine peripheral compartment temperatures and regional distribution of body heat.[5] Mean body temperature can be estimated from the combination of mean skin and core temperatures.[11]

Why Core Temperature Should Be Monitored

Core temperature monitoring is appropriate during most general anesthetics both to facilitate detection of malignant hyperthermia and to quantify hyperthermia and hypothermia. Malignant hyperthermia is best detected by an increase in end-tidal partial pressure of carbon dioxide out of proportion to minute ventilation.[12] But while core temperature is not the first sign of a malignant hyperthermia crisis, it helps confirm the diagnosis. For example, Larach *et al.* estimated that the risk of dying after a malignant hyperthermia crises was an order of magnitude higher in unmonitored patients, presumably because temperature monitoring facilitated speedy diagnosis.[13]

Most intraoperative hyperthermia does not result from malignant hyperthermia. Other, more common etiologies include excessive warming, infectious fever, blood in the fourth cerebral ventricle, and mismatched blood transfusions. Because hyperthermia has so many serious etiologies, any perioperative hyperthermia requires diagnostic attention.

By far the most common perioperative thermal disturbance is inadvertent hypothermia. Randomized trials show that even mild hypothermia causes serious complications including surgical wound infection,[14] coagulopathy and increased allogeneic transfusions,[15] and delayed postanesthetic recovery.[16] Maintaining normothermia during surgery has therefore become routine.

All general anesthetics profoundly impair thermoregulatory control, especially reducing the thresholds (triggering core temperature) for the major cold defenses, which are arterio-venous shunt constriction and shivering.[7,17] Thermoregulatory impairment combined with a cool operating room environment and surgical exposure makes nearly all unwarmed surgical patients hypothermic. Neuraxial anesthesia also impairs thermoregulation, largely by preventing vasoconstriction and shivering in blocked

Submitted for publication May 21, 2020. Accepted for publication June 29, 2020. From the Department of Outcomes Research, Cleveland Clinic, Cleveland, Ohio.

 Anesthesiology 2020; XXX:00–00. DOI: 10.1097/ALN.0000000000003481

<zdoi;. DOI: 10.1097/ALN.0000000000003481>

regions.[18] Hypothermia is thus comparably likely and profound with general and neuraxial anesthesia (for a given type of surgery)[19]—and is presumably equally harmful.

Recognizing that temperature monitoring may be impractical during short cases, the general consensus is that core temperature should be measured when general anesthesia exceeds 30 min. Core temperature should similarly be monitored when neuraxial anesthesia exceeds 30 min. In contrast, sedation and peripheral nerve blocks only minimally impair thermoregulatory control and rarely produce substantive hypothermia. Furthermore, neither approach triggers malignant hyperthermia. Temperature monitoring is thus not normally required during sedation or for peripheral nerve blocks.

Types of Thermometers

The word *thermometer* is derived from the Greek *thermos* (meaning hot) and *metron* (meaning measure). Several inventors, most notably Galileo Galilei, developed thermometers at the end of the 16th century. However, none of these devices were calibrated and could therefore only be used to estimate relative temperature differences.

The first calibrated thermometer was developed by the astronomer Olaus Roemer. That alcohol-based thermometer was considerably improved by contemporary physicist Daniel Gabriel Fahrenheit, who enclosed mercury in glass in 1714. A decade later, he developed the eponymous scale with 32°F being the freezing point for water and 212°F being the boiling point.

Although the Fahrenheit scale is still used in the United States and a few small countries, most of the world uses the scale developed by astronomer Anders Celsius, which is also referred to as the centigrade scale because it divides temperatures between the freezing and boiling points of water into a hundred degrees. The only other commonly used scale, again eponymous, was developed by Lord Kelvin; it sets 0°K at absolute zero but otherwise uses degrees of the same magnitude as the Celsius scale.

Although fever has been recognized as a sign of illness since antiquity, thermometry was not incorporated into clinical practice until 1868, when Carl Wunderlich published temperature measurements on more than 25,000 patients, correctly concluding that normal body temperature typically varies ±0.5°C from about 37°C.

Most clinical thermometers report the temperature of their sensors to within a few tenths of a degree Celsius without user calibration, which is perfectly adequate for clinical use. While there are dozens of kinds of thermometer, only four are generally available for perioperative use.

Thermistors and Thermocouples

Thermistors are simple semiconductors whose resistance varies nonlinearly with temperature. Because the relationship is consistent for a given type, resistance can be converted to absolute temperature. The conversion software for standard YSI 400 thermistors is incorporated into all multifunction anesthetic monitors. Most clinical thermometers are thermistor-based.

Thermocouples are based on the thermoelectric effect, discovered in 1831 by Thomas Seebeck. In practice, thermocouples are bimetal junctions that generate a tiny thermoelectric voltage that varies nonlinearly with temperature; because the relationship is consistent for a given metal combination, the voltage can be converted to absolute temperature. Various metals can be used, but most medical thermocouples are copper–constantan ("Type T"), which is inexpensive and sensitive in the relevant range. Constantan is a fragile copper–nickel alloy. Thermocouples are perfectly satisfactory for single-patient use, but fail after prolonged use because the constantan wire fractures.

The production cost of thermistors and thermocouples is perhaps a few cents each, although surrounding materials, such as an esophageal stethoscope, and sterile or clean processing add cost. Most are labeled for single use, but there is no particular contraindication to reuse with appropriate cleaning. Thermistors and thermocouples do not gradually fail or become progressively less accurate. Instead, they simply stop working at some point, usually when a connecting wire fails.

Infrared

All substances above absolute 0°K emit radiation, usually in the infrared range. The emitted frequency depends on emissivity of the substance and on its temperature. "Black bodies" (ideal nonreflective surfaces) absorb all incident light and emit characteristic frequencies that depend only on their temperature according to Planck's law. The term *black* refers to the fact that emission is infrared and thus invisible to humans until temperature reaches about 500°C of degrees. At 1,000°C, a black body appears red, and it becomes white at about 5,000°C. Fortunately, the lethal gamma rays produced at tens of millions of degrees in the center of the sun do not make it to the surface, which is "only" about 5,800°K.

Human tissue (of any color) has an emissivity similar to a black body, making emitted infrared radiation frequency an accurate measure of surface temperature. However, infrared thermometers have limited ability to "see" below the surface and thus represent temperature of the top millimeters of the relevant surface.

The great advantage of infrared thermometry is that it estimates temperature at a distance. Well-known applications include determining the temperature of molten metal, the temperature of stars, and scanning travelers for fever in airports. In a clinical context, tissue temperature, say of an organ surface during surgery, can be measured without direct contact and risk of contamination. Infrared imaging can be used to simultaneously assess skin temperature over the entire visible surface, which can be useful for

evaluating the effect of various warming systems or where heat is being lost or gained during various environmental exposure conditions. Infrared mapping is also used to detect inflammation and evaluate perfusion after free-flap surgery.

Zero Heat Flux

Zero-heat-flux thermometry was developed by Fox and Solman in 1970.[20] Roughly speaking, these devices consist of two thermometers separated by an insulator, covered by a heater. One thermometer is positioned between the skin surface and the lower surface of the insulator, and the other between the upper surface of the insulator and the heater. The temperature of the heater is servo-controlled to keep both thermometers at the same temperature. The Second Law of Thermodynamics specifies that heat can only flow along a temperature gradient. Because there is no temperature gradient across the insulator, there can be no flow of heat. The entire system thus becomes a perfect insulator.

Normally, there is a thermal gradient from the body core (trunk and head), where most heat is generated to the skin surface. On average, this gradient is required since it would otherwise be impossible to dissipate core heat. In the presence of a zero-heat-flux thermometer, heat flowing toward the covered surface cannot escape through the perfect insulator and therefore accumulates below the device. In theory, after some minutes of equilibration, a column of tissue at the same temperature will extend from the core to the skin surface below the zero-heat-flux thermometer. When these conditions are met, the temperature of the patient's core and thermometer are identical (fig. 1).[21]

In practice, the assumptions of zero-heat-flux thermometry are never exactly met because the column of tissue connecting the core to the skin surface and thermometer is disrupted by lateral convection of heat by flowing blood. The depth of the column depends on the width of the servo-controlled area (larger area deepens the column) and regional blood flow (greater flow makes the column shallower). Typically, the column extends about a centimeter below the skin surface. Fortunately, there are body regions where core temperature usually extends to within about a centimeter of the skin surface. The forehead is one such area, and is the site most used for zero-heat-flux thermometry.

For decades, the only commercial zero-heat-flux thermometer was made in Japan by Terumo and was not available in North America or Europe. That product is no longer sold. The only zero-heat-flux thermometer now available is from 3M (USA). It has been evaluated by various investigators and typically shown to have 95% limits of agreements of about ±0.7°C so long as core temperature perturbations are relatively slow.[22–24]

Recently, systems have been developed that do not include a heater, instead using proprietary algorithms to estimate core temperature from the difference in temperature across a known insulator.[25,26] Such systems are presumably sensitive to ambient temperature changes, including those resulting from clinical warming systems. Additional validation remains necessary to confirm that they work reliably across various clinical conditions.

Temperature Monitoring Sites

Most clinical thermometers accurately report their own temperature, and usually the temperature of adjacent tissue. It is generally accepted that the combined inaccuracy of a site/thermometer combination designed to estimate core temperature should not much exceed ±0.5°C from true core temperature. A basis for accepting this range is that it approximates the normal circadian variation, and that smaller deviations have never been shown to provoke harm. The difficulty is that tissue temperature varies considerably from region to region. Nearly all error in clinical thermometry results from selection of the measurement site rather than from inaccuracies in the thermometers *per se*.

Core

The temperature of the core thermal compartment can be evaluated in the pulmonary artery, distal esophagus, nasopharynx, or tympanic membrane because each site is well perfused with blood from the core. Even during rapid thermal perturbations (*e.g.*, cardiopulmonary bypass), these temperature-monitoring sites remain reliable—although there may be transient real differences among them.

Pulmonary artery temperature is possibly the best single estimate of core temperature, but is rarely available. The esophagus is the most obvious temperature monitoring site during general endotracheal anesthesia, but the temperature probes must be positioned at the point of maximal heart sounds or more distally to avoid cooling by respiratory gases.[27,28] The nasopharynx is an excellent alternative when esophageal monitoring is precluded for surgical reasons or blocked by a supraglottic airway. Nasopharyngeal probes need to be inserted between 10 and 20 cm past the nares to accurately estimate core temperature in adults—which is further than generally appreciated (fig. 2).[29]

Tympanic membrane probes are more difficult to insert than generally appreciated because the aural canal is several centimeters long and is not straight. The difficulty is that patients and clinicians inserting thermistors or thermocouples often mistake the bend in the canal for the tympanic membrane and thus do not insert the probes far enough to reach the membrane itself. This problem is aggravated because many commercial probes are too flexible to negotiate the length of the aural canal. The risk of puncturing the tympanic membrane is negligible; the far more common problem is that probes are not inserted sufficiently far, resulting in an inaccurate core temperature estimate.

The tympanic membrane is a true core site. Consequently, infrared signals actually obtained from the tympanic membrane are accurate. For example, incorporating an infrared sensor into an earphone appears reliable,[30,31] although such

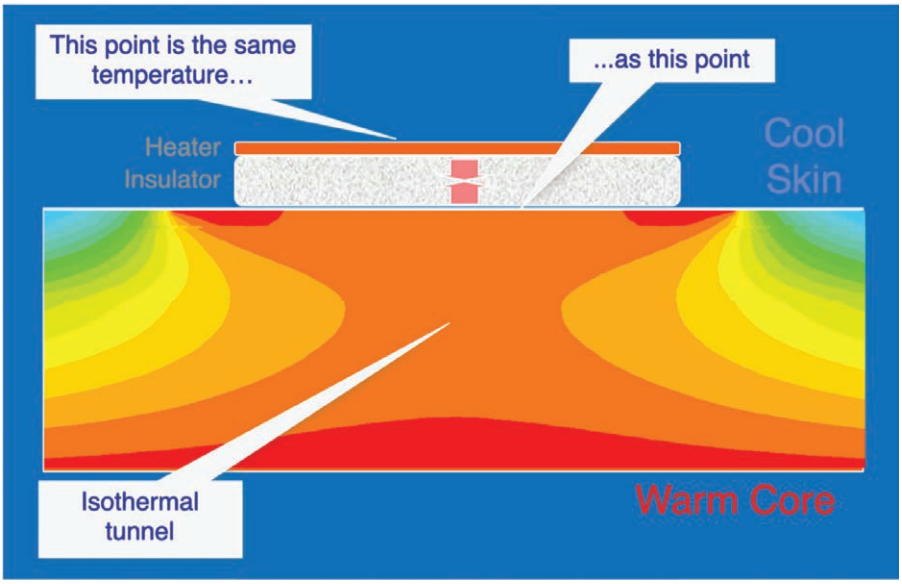

Fig. 1. Zero-heat-flux systems consist of two thermometers separated by an insulator, covered by a heater. One thermometer is positioned between the skin surface and the lower surface of the insulator, and the other between the upper surface of the insulator and the heater. The temperature of the heater is servo-controlled to keep both thermometers at the same temperature. Because there is no temperature gradient across the insulator, there can be no flow of heat, making the entire system a perfect insulator. Normally, there is a thermal gradient from the body core, where most heat is generated to the skin surface. In the presence of a zero-heat-flux thermometer, heat flowing toward the covered surface cannot escape through the perfect insulator and therefore accumulates below the device. In theory, after some minutes of equilibration, a column of tissue at the same temperature will extend from the core to the skin surface below the zero-heat-flux thermometer. When these conditions are met, temperature of the core and thermometer are identical. Because of lateral convection of heat by blood, the column typically extends only about a centimeter below the skin surface—but on the forehead, that is deep enough to approximate core temperature.

systems are not generally available. The difficulty is that nearly all clinical infrared aural canal thermometers are intentionally too large to even fit more than a few millimeters into the aural canal and therefore do not "see" the tympanic membrane. As normally used, that is directed into the aural canal, infrared aural canal "tympanic membrane" systems essentially measure skin temperature and therefore poorly estimate core temperature.[32] In light of their poor performance, it seems unfortunate that infrared aural canal systems have become so popular.

Core temperature can also be obtained from ingested capsules that transmit temperatures to a nearby antenna, usually worn as a vest. These systems are rarely used for routine practice, but are invaluable when it is necessary to reliably measure core temperature over days, say for studies of circadian rhythms.[33]

Near-core

There are various sites that, under appropriate circumstances, reasonably estimate core temperature. Carefully acquired oral and axillary[34] temperatures, for example, are usually close to core temperature.[35] Both can reasonably be used for most patients recovering from anesthesia. A more sophisticated axillary thermometer measures temperature at the skin surface and on the reverse side of the device, allowing it to compensate for changes in arm position and ambient temperature.[36]

In contrast, bladder and rectal temperatures are less reliable because both sites are poorly perfused and thus appreciably lag core temperature during rapid thermal perturbations. Bladder temperature especially lags core temperature when urine flow is low.[37] The "intermediate" nature of these sites can be helpful for assessing the adequacy of peripheral rewarming during cardiopulmonary bypass. But they are poor indicators of core temperature. For example, consider swine the size of adult humans having malignant hyperthermia crises. Within 30 min, pulmonary artery and esophageal temperatures were nearly 40°C and the animals near death, but rectal temperatures were essentially unchanged. Rectal temperature therefore completely failed in one of its key purposes, helping diagnose malignant hyperthermia (fig. 3).[38] Rectal temperature also often fails to accurately reflect core temperature under other circumstances including heat stroke.[39,40] There is probably less of a lag between core and the bladder or rectum in infants and small children, making both sites reasonable for many pediatric indications.

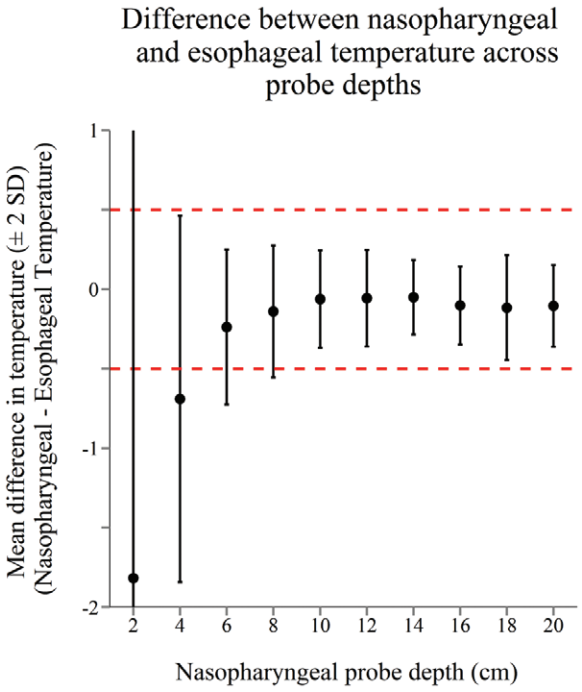

Fig. 2. The difference between distal esophageal (reference) temperature and nasopharyngeal temperature as a function of probe insertion depth past the nares in adult surgical patients. Nasopharyngeal temperatures were accurate at insertion depths between 10 and 20 cm, defined by being within ±0.5°C of esophageal temperature. Reprinted with permission from Wang *et al.*[29]

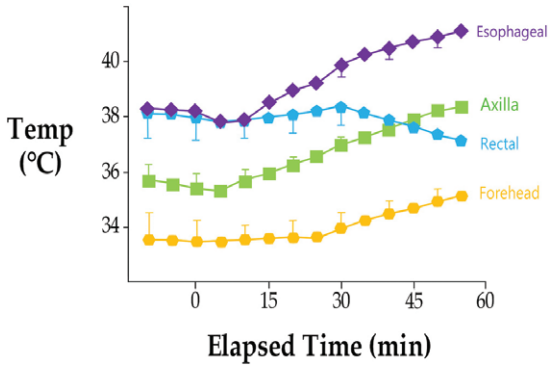

Fig. 3. Malignant hyperthermia susceptible swine the size of adult humans were given halothane and succinylcholine at elapsed time 0. Within 15 min, arterial partial pressure of carbon dioxide exceeded 90 mmHg, and arterial pH was less than 6.9. Esophageal and axillary temperatures rapidly increased; rectal and forehead temperatures did not. Rectal and skin temperature therefore failed to identify lethal malignant hyperthermia crises. Modified from Iaizzo *et al.* with permission.[38]

Skin

Skin temperature is determined by the balance of heat provided by subcutaneous tissues and heat lost to the environment. Heat from the skin surface is mostly dissipated by radiation and convection, with conduction and evaporation usually contributing little. While each type of heat loss is controlled by different mostly nonlinear equations, cutaneous heat loss is approximately a linear function of the difference between skin and ambient temperature over small ranges.

Skin surface temperatures are considerably lower than core temperature[41]; forehead skin temperature, for example, is typically 2°C cooler than core temperature in hospital environments. Unfortunately, the core-to-forehead skin temperature difference varies among individuals and over time. The main determinant of change is ambient temperature rather than vasomotion.[8] Consequently, simply adding a fixed compensation, such as 2°C, to skin temperature does not reliably estimate core temperature.[42]

A special case of skin temperature monitoring is temporal artery thermometers. These are infrared skin surface thermometers that record skin temperature at approximately 10 Hz and detect the highest temperature as the device is scanned across the forehead, including the region of the temporal artery. The theory is that the blood in the temporal artery is near core temperature and, therefore, that supervening skin temperature will also approximate core temperature. While the theory is attractive, device accuracy is inconsistent.[35,43,44] As with infrared aural canal thermometers, their popularity seems unfortunate.

Conclusions

Nearly all unwarmed patients become hypothermic during general or neuraxial anesthesia, and the amount of hypothermia is similar with each type of anesthesia. There is considerable evidence that mild hypothermia causes serious complications, with coagulopathy being the best documented. Temperature monitoring guides perioperative thermal management and helps detect fever and malignant hyperthermia.

Medical thermometers accurately estimate temperature of adjacent tissue; the difficulty is that few core sites are accessible and that tissue temperatures in other sites are lower than core temperature by variable amounts—and that the difference changes over time. The esophagus and nasopharynx are usually the best practical temperature monitoring sites during general anesthesia. Both are true core sites, and they are both resistant to artifact. Alternatives suitable for neuraxial anesthesia and postoperative care include oral and axillary temperatures, along with zero-heat flux forehead temperature.

Uncompensated skin temperature or skin temperature adjusted by adding a constant are not reliable ways

of estimating core temperature. Temporal artery scanning and infrared aural canal thermometers are also inconsistent. Rectal and bladder temperatures are suboptimal in adults because they can substantially lag core temperature during rapid thermal perturbations.

In summary, most unwarmed surgical patients become hypothermic, and hypothermia causes complications. The purpose of temperature monitoring is to detect thermal disturbances and maintain appropriate body temperature during anesthesia. Core body temperature should be measured or reliably estimated in most patients given general or neuraxial anesthesia for more than 30 min. Unless hypothermia is specifically indicated (*e.g.*, for protection against ischemia), efforts should be made to maintain intraoperative core temperature greater than 36°C.[45]

Information Sources

The author supplemented his personal collection of published temperature-related articles (n > 2,250) with a search of the Medline database (years 2009 to 2019). The specific search terms were as follows: ((Perioperative Period[MeSH] OR Perioperative Care[MeSH] OR perioperative[title] OR preoperative[title] OR intraoperative[title] OR postoperative[title) AND (Body Temperature[MeSH] OR temperature[title]) AND (Physiologic Monitoring[MeSH] OR monitor*[title])) AND ((Perioperative Period[MeSH] OR Perioperative Care[MeSH] OR perioperative[title] OR preoperative[title] OR intraoperative[title] OR postoperative[title) AND (Thermometry[MeSH] OR "zero heat flux"[title] OR thermomet*[ti] OR thermistor*[title] OR thermocouple*[ti])) AND (Intraoperative Monitoring[MeSH] AND (Body Temperature[MeSH] OR temperature[title])).

Apparently relevant references from within citation lists were also considered. All articles were considered; those with the most robust methodology and largest sample size were given most weight. In general, the most reliable evidence is cited, with the most recent being cited when comparable articles provide evidence for a given point. Major reviews are cited to provide additional details and references. Articles were selected for citation based on the author's impression of their importance.

Research Support

Support was provided solely from institutional and/or departmental sources.

Competing Interests

Dr. Sessler serves on advisory boards for 3M (St. Paul, Minnesota), 37 Company (Amersfoort, The Netherlands), and Calorint/TransQtronic (Philadelphia, Pennsylvania), and consults for Mercury Medical (Cleveland, Ohio) and GenTherm (Northville, Michigan). He donates all these fees to charity and thus has no personal financial interests related to this review. 3M funds Dr. Sessler's research.

Correspondence

Address correspondence to Dr. Sessler: Department of Outcomes Research, Anesthesiology Institute, Cleveland Clinic, 9500 Euclid Ave — P77, Cleveland, Ohio 44195. DS@OR.org. Anesthesiology's articles are made freely accessible to all readers, for personal use only, 6 months from the cover date of the issue.

References

1. Sessler DI: Temperature monitoring and perioperative thermoregulation. Anesthesiology 2008; 109:318–38
2. Sessler DI: Perioperative heat balance. Anesthesiology 2000; 92:578–96
3. Sessler DI: Complications and treatment of mild hypothermia. Anesthesiology 2001; 95:531–43
4. Tayefeh F, Plattner O, Sessler DI, Ikeda T, Marder D: Circadian changes in the sweating-to-vasoconstriction interthreshold range. Pflugers Arch 1998; 435:402–6
5. Kurz A, Sessler DI, Christensen R, Dechert M: Heat balance and distribution during the core-temperature plateau in anesthetized humans. Anesthesiology 1995; 83:491–9
6. Rajek A, Lenhardt R, Sessler DI, Kurz A, Laufer G, Christensen R, Matsukawa T, Hiesmayr M: Tissue heat content and distribution during and after cardiopulmonary bypass at 31 degrees C and 27 degrees C. Anesthesiology 1998; 88:1511–8
7. Matsukawa T, Kurz A, Sessler DI, Bjorksten AR, Merrifield B, Cheng C: Propofol linearly reduces the vasoconstriction and shivering thresholds. Anesthesiology 1995; 82:1169–80
8. Ikeda T, Sessler DI, Marder D, Xiong J: Influence of thermoregulatory vasomotion and ambient temperature variation on the accuracy of core-temperature estimates by cutaneous liquid-crystal thermometers. Anesthesiology 1997; 86:603–12
9. Rubinstein EH, Sessler DI: Skin-surface temperature gradients correlate with fingertip blood flow in humans. Anesthesiology 1990; 73:541–5
10. Heier T, Caldwell JE: Impact of hypothermia on the response to neuromuscular blocking drugs. Anesthesiology 2006; 104:1070–80
11. Lenhardt R, Sessler DI: Estimation of mean body temperature from mean skin and core temperature. Anesthesiology 2006; 105:1117–21
12. Larach MG, Gronert GA, Allen GC, Brandom BW, Lehman EB: Clinical presentation, treatment, and complications of malignant hyperthermia in North America from 1987 to 2006. Anesth Analg 2010; 110:498–507
13. Larach MG, Brandom BW, Allen GC, Gronert GA, Lehman EB: Malignant hyperthermia deaths related to inadequate temperature monitoring, 2007-2012: A

report from the North American malignant hyperthermia registry of the malignant hyperthermia association of the United States. Anesth Analg 2014; 119:1359–66
14. Kurz A, Sessler DI, Lenhardt R: Perioperative normothermia to reduce the incidence of surgical-wound infection and shorten hospitalization. Study of Wound Infection and Temperature Group. N Engl J Med 1996; 334:1209–15
15. Rajagopalan S, Mascha E, Na J, Sessler DI: The effects of mild perioperative hypothermia on blood loss and transfusion requirement. Anesthesiology 2008; 108:71–7
16. Lenhardt R, Marker E, Goll V, Tschernich H, Kurz A, Sessler DI, Narzt E, Lackner F: Mild intraoperative hypothermia prolongs postanesthetic recovery. Anesthesiology 1997; 87:1318–23
17. Xiong J, Kurz A, Sessler DI, Plattner O, Christensen R, Dechert M, Ikeda T: Isoflurane produces marked and nonlinear decreases in the vasoconstriction and shivering thresholds. Anesthesiology 1996; 85:240–5
18. Matsukawa T, Sessler DI, Christensen R, Ozaki M, Schroeder M: Heat flow and distribution during epidural anesthesia. Anesthesiology 1995; 83:961–7
19. Frank SM, Shir Y, Raja SN, Fleisher LA, Beattie C: Core hypothermia and skin-surface temperature gradients. Epidural *versus* general anesthesia and the effects of age. Anesthesiology 1994; 80:502–8
20. Fox RH, Solman AJ: A new technique for monitoring the deep body temperature in man from the intact skin surface. J Physiol (US) 1970; 212:8–10
21. Yamakage M, Namiki A: Deep temperature monitoring using a zero-heat-flow method. J Anesth 2003; 17:108–15
22. Eshraghi Y, Nasr V, Parra-Sanchez I, Van Duren A, Botham M, Santoscoy T, Sessler DI: An evaluation of a zero-heat-flux cutaneous thermometer in cardiac surgical patients. Anesth Analg 2014; 119:543–9
23. Boisson M, Alaux A, Kerforne T, Mimoz O, Debaene B, Dahyot-Fizelier C, Frasca D: Intra-operative cutaneous temperature monitoring with zero-heat-flux technique (3M SpotOn) in comparison with oesophageal and arterial temperature: A prospective observational study. Eur J Anaesthesiol 2018; 35:825–30
24. Kollmann Camaiora A, Brogly N, Alsina E, de Celis I, Huercio I, Gilsanz F: Validation of the Zero-Heat-Flux thermometer (SpotOn®) in major gynecological surgery to monitor intraoperative core temperature: A comparative study with esophageal core temperature. Minerva Anestesiol 2019; 85:351–7
25. Evron S, Weissman A, Toivis V, Shahaf DB, You J, Sessler DI, Ezri T: Evaluation of the Temple Touch Pro, a novel noninvasive core-temperature monitoring system. Anesth Analg 2017; 125:103–9
26. Kitamura K, Zhu X, Chen W, Nemoto T: Development of a new method for the noninvasive measurement of deep body temperature without a heater. Med Eng Phys 2010; 32:1–6
27. Kaufman RD: Relationship between esophageal temperature gradient and heart and lung sounds heard by esophageal stethoscope. Anesth Analg 1987; 66:1046–8
28. Bloch EC, Ginsberg B, Binner RA Jr: The esophageal temperature gradient in anesthetized children. J Clin Monit 1993; 9:73–7
29. Wang M, Singh A, Qureshi H, Leone A, Mascha EJ, Sessler DI: Optimal depth for nasopharyngeal temperature probe positioning. Anesth Analg 2016; 122:1434–8
30. Kiya T, Yamakage M, Hayase T, Satoh J, Namiki A: The usefulness of an earphone-type infrared tympanic thermometer for intraoperative core temperature monitoring. Anesth Analg 2007; 105:1688–92, table of contents
31. Masamune T, Yamauchi M, Wada K, Iwashita H, Okuyama K, Ino H, Yamakage M, Ishiyama T, Matsukawa T: The usefulness of an earphone-type infrared tympanic thermometer during cardiac surgery with cardiopulmonary bypass: Clinical report. J Anesth 2011; 25:576–9
32. Imamura M, Matsukawa T, Ozaki M, Sessler DI, Nishiyama T, Kumazawa T: The accuracy and precision of four infrared aural canal thermometers during cardiac surgery. Acta Anaesthesiol Scand 1998; 42:1222–6
33. Sessler DI, Lee KA, McGuire J: Isoflurane anesthesia and circadian temperature cycles in humans. Anesthesiology 1991; 75:985–9
34. Lodha R, Mukerji N, Sinha N, Pandey RM, Jain Y: Is axillary temperature an appropriate surrogate for core temperature? Indian J Pediatr 2000; 67:571–4
35. Langham GE, Maheshwari A, Contrera K, You J, Mascha E, Sessler DI: Noninvasive temperature monitoring in postanesthesia care units. Anesthesiology 2009; 111:90–6
36. Pei L, Huang Y, Mao G, Sessler DI: Axillary temperature, as recorded by the iThermonitor WT701, well represents core temperature in adults having noncardiac surgery. Anesth Analg 2018; 126:833–8
37. Horrow JC, Rosenberg H: Does urinary catheter temperature reflect core temperature during cardiac surgery? Anesthesiology 1988; 69:986–9
38. Iaizzo PA, Kehler CH, Zink RS, Belani KG, Sessler DI: Thermal response in acute porcine malignant hyperthermia. Anesth Analg 1996; 82:803–9
39. Ash CJ, Cook JR, McMurry TA, Auner CR: The use of rectal temperature to monitor heat stroke. Mo Med 1992; 89:283–8
40. Buck SH, Zaritsky AL: Occult core hyperthermia complicating cardiogenic shock. Pediatrics 1989; 83:782–4
41. Burgess GE 3rd, Cooper JR, Marino RJ, Peuler MJ: Continuous monitoring of skin temperature using a liquid-crystal thermometer during anesthesia. South Med J 1978; 71:516–8

42. Simpson G, Rodseth RN: A prospective observational study testing liquid crystal phase change type thermometer placed on skin against oesophageal/pharyngeal placed thermometers in participants undergoing general anesthesia. BMC Anesthesiol 2019; 19:206
43. Greenes DS, Fleisher GR: Accuracy of a noninvasive temporal artery thermometer for use in infants. Arch Pediatr Adolesc Med 2001; 155:376–81
44. Niven DJ, Gaudet JE, Laupland KB, Mrklas KJ, Roberts DJ, Stelfox HT: Accuracy of peripheral thermometers for estimating temperature: A systematic review and meta-analysis. Ann Intern Med 2015; 163:768–77
45. Sessler DI: A proposal for new temperature monitoring and thermal management guidelines. Anesthesiology 1998; 89:1298–300