Anesthesiology
73:218–224, 1990

Skin-Surface Warming: Heat Flux and Central Temperature

Daniel I. Sessler, M.D., Azita Moayeri, B.A.†*

The authors determined the efficacy of four postoperative warming devices by measuring cutaneous and tympanic membrane temperatures, and heat loss/gain using 11 thermocouples and ten thermal flux transducers in five healthy, unanesthetized volunteers. Overall thermal comfort was evaluated at 5–10-min intervals using a 10-cm visual analog scale. The warming devices were: 1) a pair of 250-W infrared heating lamps mounted 71 cm above the abdomen; 2) the Thermal Ceiling® MTC XI UL (500 W) set on "high" and mounted 56 cm above the volunteer; 3) a 54-by-145-cm circulating-water blanket set to 40° C placed over the volunteer; and 4) the Bair Hugger® forced air warmer with an adult-sized cover set on "low" (≈33° C), "medium" (≈38° C), and "high" (≈43° C). Following a 10-min control period, each device was placed over the volunteer and activated for a 30-min period. All devices were started "cold" and warmed up during the study period. The Bair Hugger® set on "medium" decreased heat loss more than each radiant warming device and as much as the circulating-water blanket. All methods reached maximum efficacy within 20 min. Set on "high," the Bair Hugger® increased skin-surface temperature more than the circulating-water blanket. The Bair Hugger® (all settings) and the water blanket raised skin temperature more than the radiant heaters. The circulating-water blanket was the most effective device for heating an optimally placed transducer on the chest (directly under and parallel to the radiant heat sources, and touching the water and Bair Hugger® blankets). However, when the entire skin surface was considered, the Bair Hugger® set on "high" transferred the most heat, enough to increase mean body temperature ≈ 1.5° C/h in a postoperative patient without thermoregulatory responses. Central temperature decreased slightly (the expected thermoregulatory response) during skin-surface warming, the decrease being roughly in proportion to the efficacy of the warming devices. Cutaneous heat flux correlated well with skin-surface temperature, but not with thermal comfort. There was no correlation between forehead and tympanic membrane temperatures. (Key words: Equipment: warming devices. Measurement techniques, heat: thermal flux transducers. Temperature, hypothermia: postoperative.)

ANESTHETIZED surgical patients frequently become hypothermic.[1] During the recovery period, mild hypothermia prolongs the effect of some drugs[2] and may trigger a shivering-like tremor that increases discomfort and metabolic stress.[3] In adults, central hypothermia also may prolong the duration, and thus the cost, of recovery (although prolonged recovery has yet to be proven).

Because most metabolic heat is lost through skin[4] (a small fraction is respiratory[5,6]), effective noninvasive rewarming of patients requires decreasing cutaneous heat loss. Although thermal flux across skin is largely determined by skin temperature, heat loss cannot easily be calculated directly from skin temperature. Furthermore, heat transfer cannot be determined only by changes in central body temperature because this temperature is influenced by thermoregulatory responses and redistribution of heat within the body.

To determine the efficacy of four postoperative warming devices, we therefore measured cutaneous heat loss/gain using thermal flux transducers in unanesthetized volunteers. We took this opportunity to also evaluate the correlation between forehead skin-surface temperature and tympanic membrane temperature.

Methods

With approval from the University of California, San Francisco Committee on Human Research and written consent from volunteers, we evaluated cutaneous heat transfer in three women and two men aged 26–37 yr. None was obese, taking medication, or had a history of thyroid disease, dysautonomia, or Raynaud's syndrome. The volunteers were minimally clothed and reclined on a standard operating room table during the study. Ambient temperatures were maintained at 20.6 ± 0.5° C and relative humidity near 35%.

We studied four warming devices: 1) a pair of 250-W infrared heating lamps mounted 71 cm above the abdomen (W.T. Farley, Inc., Simi Valley, CA); 2) the Thermal Ceiling® MTC XI UL (500 W) set on "high" and mounted 56 cm above the volunteer (Aragona Medical, Inc, River Vale, NJ); 3) a 54-by-145-cm circulating-water blanket (Blanketrol, Sub Zero Products, Inc., Cincinnati, OH) set to 40° C placed over the volunteer; and 4) the Bair Hugger® Model 200 forced air warmer (Augustine Medical, Inc., Eden Prairie, MN) with an adult-sized cover set on "low" (≈33° C), "medium" (≈38° C), and "high" (≈43° C). The Bair Hugger® warmer injects warm air into a disposable plastic/paper quilt-like blanket. The warm air exits slits in the patient side of the blanket, providing a shell of warm air (microenvironment) around the subject. Both radiant heaters were separated from the volunteers by the distance recommended by the manufacturers. The water blanket was placed over, instead of under, volunteers because little heat is lost through the 5 cm of foam padding covering most operating room tables (gurnies

---

* Assistant Professor of Anesthesia.

† Staff Research Associate.

Received from the Department of Anesthesia, University of California, San Francisco, San Francisco, California.

This study was supported by Augustine Medical, Inc.; Dr. Sessler is a consultant for this company. Presented in part at the Annual Meeting of the American Society of Anesthesiologists, New Orleans, 1989.

Address reprint requests to Dr. Sessler: Department of Anesthesia, Room C-450, University of California, San Francisco, California 94143-0648.

and beds used in recovery areas probably provide even better insulation).[4]

Following a 10-min control period, each device was placed over the volunteer and activated for 30 min. The warmers were started "cold" and allowed to warm during the study period. The devices were evaluated in random order; adequate cooling of the Bair Hugger® was assured by not using it in adjacent test periods. Enough time was allowed between measurements (*e.g.*, 30–90 min) to assure that cutaneous temperatures and heat flux returned to baseline values.

Heat flux from ten skin-surface sites was measured in W/m^2 using thermal flux transducers (Thermonetics, San Diego, California). These values were converted into watts/site by multiplying by the calculated body surface area [$\text{area}(m^2) = \text{weight}^{0.425}(\text{kg}) \cdot \text{height}^{0.725}(\text{cm}) \cdot 0.007184$] of each volunteer and assigning the following regional percentages: head 6%; upper arms 9%; forearms 6%; hands 4.5%; back 19%; chest 9.5%; abdomen 9.5%; thigh 19%; calves 11.5%; feet 6%.[7]

The transducers were 25 mm-diameter circles, except those placed on the head, hand, and abdomen, which measured 9-by-18 mm. All were firmly affixed to the skin surface with a ring of thin, double-sided adhesive film (3M, Inc., St. Paul, MN) having trivial thermal resistance.

Thermal flux transducers, in effect, compare temperatures on each side of a known thermal resistance. (The transducers are actually calibrated thermopiles that produce a voltage proportional to flux.) Heat flux transducers measure total heat loss (or gain) *via* radiation, conduction, and convection; they do not detect evaporative losses. However, sweating was observed only at the end of Bair Hugger® warming at the "high" setting. Sweating would not be expected during normal clinical use because only hypothermic patients would be vigorously rewarmed.

Physical properties of the transducers include: emissivity = 0.9, thermal conductivity = $0.0026\ W \cdot {}^\circ C^{-1} \cdot cm^{-1}$, and a specific heat = $0.35\ cal \cdot {}^\circ C^{-1} \cdot g^{-1}$, which allows rapid detection of physiological changes in flux. The transducers are calibrated by the manufacturer who specifies that they are accurate to within 15% of absolute value. Estimates of total body heat flux obtained using Thermonetics heat flux transducers correlate well with values measured using direct calorimetry.[8]

All sensors were exposed to room air (except when covered by the circulating-water blanket or Bair Hugger® warmer). We defined flux as positive when heat traversed skin to the environment and negative when heat was absorbed from warming devices. Output from the transducers (±4 mV) was amplified 2,000-fold using a simple laboratory-built device.

Skin temperatures under each heat flux transducer were monitored using bare-wire Mon-a-Therm® (St. Louis, MS) thermocouple probes. A bare-wire probe was also used to measure ambient temperatures. Tympanic membrane temperatures were measured with flexible, cotton-covered probes. The probes were connected to Mallinckrodt® Model 8700 (St. Louis, MS) two-channel electronic thermometers with analog output. The manufacturer specifies that these thermometers have an accuracy of ≈0.1° C; extensive calibrations in our laboratory have confirmed this value. A ten-site average skin-surface temperature[9] was calculated using the same regional percentages as in the heat flux calculations.[7]

Analog data from the thermometers and heat flux transducers were acquired using an electrically isolated Macintosh® II computer (Apple, Inc., Cupertino, CA) equipped with two NB-MIO-16L® 16-channel analog-digital converters (National Instruments, Inc., Austin, TX). Data were digitized asynchronously at 2 Hz in 48-s epochs and scaled to °C and W/site using individual first- or second-order corrections and the calculated body surface area. The results were averaged, displayed graphically on the computer screen, and recorded in spreadsheet format on a hard disk at ≈2-min intervals. Only data free of electrical and other artifacts were recorded and analyzed. The process was controlled by a "virtual instrument" written using LabVIEW® graphical signal processing software (National Instruments, Inc., Austin, TX).‡

Overall thermal comfort was evaluated at 5–10-min intervals using a 100-mm visual analog scale on which 0 mm was defined as worst imaginable cold, 50 mm as thermally neutral, and 100 mm as insufferably hot. A new, unmarked scale was used for each assessment.

For statistical analysis, data were averaged into 10-min observation periods, with 0–10 min representing the control period and 11–20, 21–30, and 31–40 min identifying 30 min of warming. Changes in heat flux, average skin-surface temperature, and central temperature over time produced by each warming method were analyzed using repeated-measures ANOVA and Dunnett's tests. Differences between the devices at each time were evaluated using repeated-measures ANOVA and Scheffé's F tests. Correlations between total heat flux and average skin-surface temperature, between heat flux and thermal comfort, and between forehead and tympanic membrane temperatures were evaluated using Pearson's product-moment correlation. Data are expressed as means ± SD; $P < 0.05$ identified statistically significant differences.

Results

The mean age of the volunteers was 30 ± 4 yr, weight was 59 ± 12 kg, and height was 163 ± 6 cm. Average

---

‡ Ponte J, Sessler DI: Quantifying thermoregulatory responses. Scientific Computing and Automation February:35–39, 1989. The authors will make this program available to interested investigators.

ambient temperature was 21 ± 0.4° C. Results were similar in male and female volunteers.

The Bair Hugger® set on "medium" was more effective than each radiant warming device and as effective as the circulating-water blanket (fig. 1). All methods reached maximum efficacy within 20 min. Total heat flux was not significantly different during the control periods preceding tests of each device. During the 11–20 min data acquisition period, flux produced by each device (and the Bair Hugger® at each setting) was significantly different than the others, except between the Thermal Ceiling® and water blanket. During the 21–30 and 31–40 min periods, flux produced by each device was significantly different than the others, except between the Bair Hugger® set on "low" or "medium" and the water blanket, and between the two radiant heat sources. Flux produced by each device differed from flux during the preceding control period at each time interval.

Average skin temperatures were not significantly different during the control periods preceding tests of each device. Skin-surface temperature was increased more by the Bair Hugger® set at "high" than by the circulating-water blanket (fig. 2). The Bair Hugger® (all settings) and the water blanket raised skin temperature more than the radiant heaters. During the 11–20-min period, the Bair Hugger® set on "low," "medium," and "high" produced significantly higher skin temperatures than the Thermal Ceiling®. During the 31–40-min period, skin warming produced by each device was significantly different than the others, except between the Bair Hugger® set on "low" or "medium" and the water blanket, and between the two radiant heat sources. Skin temperature with each device differed from the temperature during the preceding control period at each time interval, except for the Thermal Ceiling® and water blanket at 11–20 min.

Tympanic membrane temperature decreased during most of the device trials, the decrease being roughly proportional to warmer efficacy (fig. 3). (Although counterintuitive, this is a normal thermoregulatory response, as unanesthetized individuals redistribute heat within the body to maintain a constant mean body temperature.)

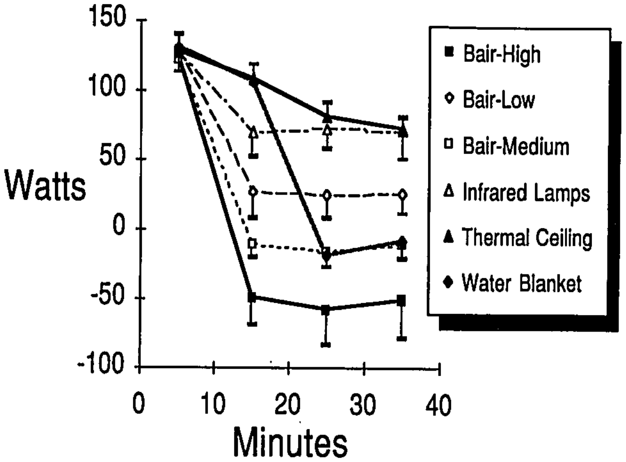

FIG. 1. Total heat flux (in W/volunteer) during the control periods (0–10 min) and 30 min of warming (11–40 min) using each method. The Bair Hugger® on the medium setting was more effective than each radiant warming device and as effective as the circulating water blanket.

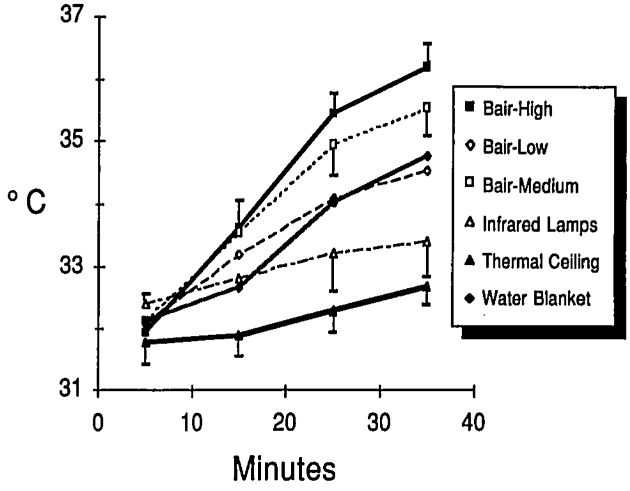

FIG. 2. Average skin-surface temperature from ten sites during the control periods (0–10 min) and 30 min of warming (11–40 min) using each method. Skin temperature was increased more by the Bair Hugger® on the high setting than by the circulating water blanket. The Bair Hugger® (all settings) and the water blanket raised skin temperature more than the radiant heaters.

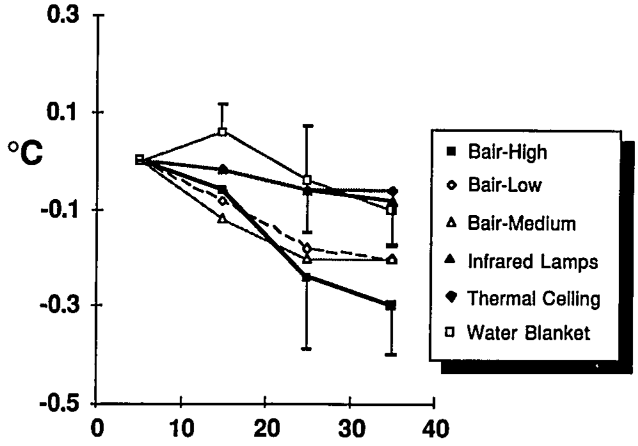

FIG. 3. Change in tympanic membrane temperature during the control periods (0–10 min) and 30 min of warming (11–40 min) using each method. Central temperature decreased during most of the device trials, the decrease being roughly proportional to warmer efficacy. The temperature decrease was significant for the Bair Hugger® between the 21–30 and 31–40 min warming periods and for the water blanket during the 31–40 min period.

Central temperatures decreased significantly with the Bair Hugger® on each setting in the 21–30- and 31–40-min warming periods. Temperature also decreased significantly with the water blanket during the 31–40-min period.

Total heat flux (W) correlated well with average skin-surface temperature (°C) (fig. 4). The variables were related by the equation: flux = 1493 − 43(temperature); r = 0.79.

Most devices will produce maximal heat flux across skin that is directly under, and parallel to, the radiant heat sources (or touching one of the warming blankets). We thus separately evaluated flux from an optimally placed transducer on the chest during the control periods and 30 min of warming using each method (fig. 5). The circulating-water blanket was the most effective warming device when only this optimally placed transducer was considered. The Thermal Ceiling® also was more effective in this trial than in warming the entire body.

Heat flux across the chest was not significantly different during the control periods preceding tests of each device. During the 11–20-min period, only the flux produced by the Bair Hugger® on "high" and the Thermal Ceiling® differed significantly. During the 31–40-min period, only the flux produced by the infrared lamps and the water blanket differed significantly. Flux produced by each device differed from flux during the preceding control period at each time interval, except for the Thermal Ceiling® and water blanket at 11–20 min.

There was little correlation between thermal comfort and total heat flux (correlation coefficients ranging from 0.56 to 0.93 [typically ≈0.7]) (fig. 6). There was no correlation between forehead skin-surface temperature (°C) and tympanic membrane temperature (°C); forehead = 0.67(tympanic) + 9.8; r = 0.29 (fig. 7).

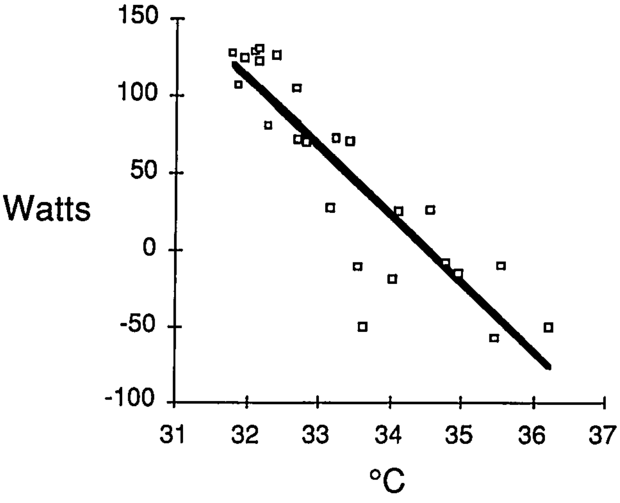

FIG. 4. Total heat flux (W) correlated well with average skin-surface temperature (°C): Flux = 1493 − 43 (temperature); r = 0.79.

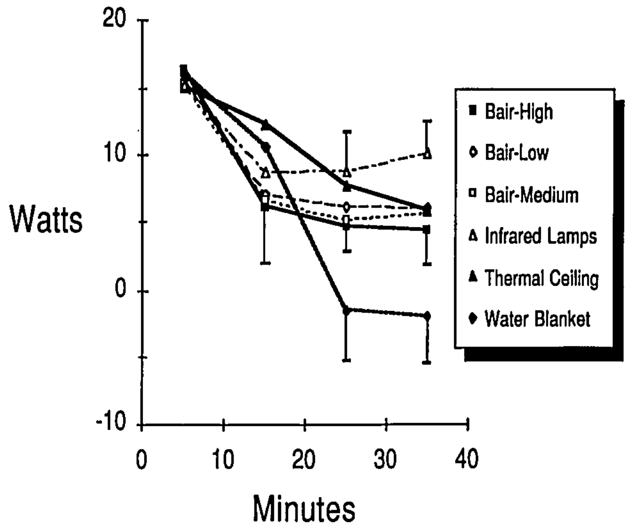

FIG. 5. Heat flux from an optimally placed transducer on the chest (directly under and parallel to the radiant heat sources and touching the warming blankets) during the control periods (0–10 min) and 30 min of warming (11–40 min) using each method. The circulating water blanket was the most effective device when only this optimally placed transducer was considered. The Thermal Ceiling® also was more effective in this trial than in warming the entire body.

Discussion

Intraoperative hypothermia is difficult to avoid because: 1) cold exposure increases environmental heat loss; 2) general anesthesia decreases metabolic heat production; and 3) anesthetic drugs inhibit thermoregulatory responses.[10–12] After anesthesia and surgery, rapid rewarming may be desirable to minimize potential complications

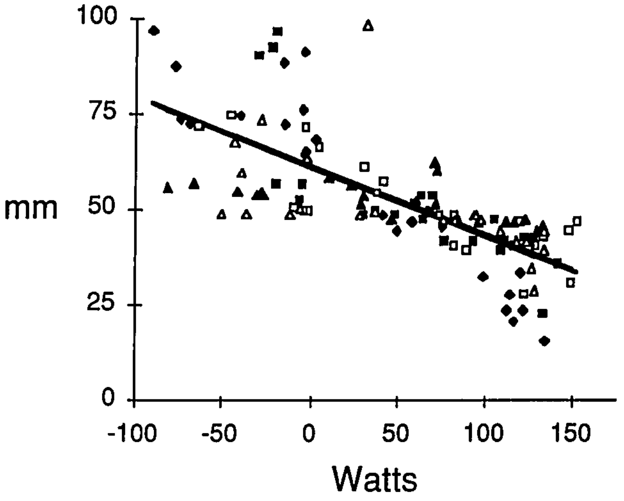

FIG. 6. There was a relatively poor correlation between thermal comfort (mm on a visual analogue scale) and total heat flux (W/volunteer). Data for each volunteer are illustrated using different symbols. Correlations between thermal comfort and heat flux in individual volunteers was little better, with correlation coefficients ranging from 0.56 to 0.93 (typically ≈ 0.7).

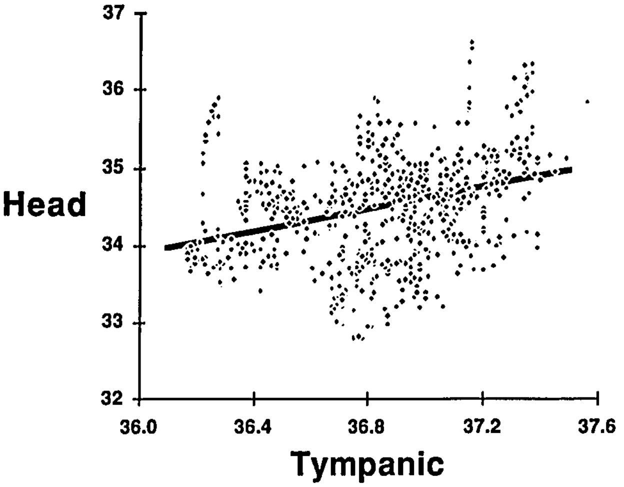

FIG. 7. There was no correlation between forehead skin-surface temperature and tympanic membrane temperature: Forehead = 0.67 (typmanic) + 9.8; r = 0.29.

of hypothermia and decrease recovery duration. Warming also may prevent thermoregulatory responses to cold (vasoconstriction, nonshivering thermogenesis, and shivering) that increase patient discomfort and metabolic stress.[3]

Thermal steady state occurs when metabolic heat production equals heat loss to the environment.[1] The basal metabolic rate in adult humans is ≈100 W (1 W = 0.86 kcal/h), and the specific heat of humans is ≈0.83 kcal · kg^{-1}°C^{-1}.[13] Actual heat production is slightly lower during general anesthesia, but may be two- to threefold higher in patients experiencing postanesthetic tremor.[14–16]

Because respiratory losses account for only 5–10 W,[17] cutaneous losses are the primary determinant of heat balance. Mean body temperature (mean ≈ 0.66*Central + 0.34*Skin).[18,§] will remain constant (with normal metabolic heat production) when ≈90 W is lost to the environment across the skin. Increasing mean body temperature 1° C/h (in adults with normal heat production) only requires preventing environmental loss of metabolic heat. Similarly, increasing temperature 2° C/h requires transfer of ≈90 W into the body.

Heat flux from our volunteers during the control periods was ≈25% greater than the estimated basal metabolic heat production. Mean body temperature would, therefore, be expected to decrease at 0.25° C/h in the absence of thermoregulatory responses. (Regulatory responses including nonshivering thermogenesis and shivering would certainly occur in normal volunteers, but are frequently inhibited by residual anesthetic in patients.[3])

The Bair Hugger® set on "low" or "medium" and the circulating-water blankets each decreased cutaneous heat loss to nearly zero, which would increase mean body temperature ≈1° C/h in postoperative patients with normal metabolic rates. The Bair Hugger® set on "high" was the most effective warmer and would be expected to increase mean body temperature ≈1.5° C/h in similar patients. Even effective transcutaneous heat transfer into the peripheral thermal compartment may not increase central temperature rapidly. The peripheral-to-central heat transfer may be particularly slow in vasoconstricted postoperative ptients.

The central thermoregulatory system responds to thermal input from tissues throughout the body.[19–23] As a result, regulatory responses to thermal perturbations, particularly those producing large temperature gradients within the body, may be difficult to predict. In general, regulatory responses are determined by mean body temperature, not simply central temperature.[24–26] (An exception to this rule is behavioral thermoregulation, which is mediated almost entirely by skin temperature.[27–29])

Skin-surface cooling increases central temperature in rats *via* shivering and nonshivering thermogenesis,[30] resulting in unchanged mean body temperature. Similarly, skin-surface warming decreases central temperature in rats.[31] The volunteers in this study demonstrated a similar response: cutaneous warming decreased central temperature, again resulting in minimal change in mean body temperature. Decreased central temperature resulted initially from thermoregulatory vasodilation and redistribution of heat within the body.[27] Because redistribution is a short-lived compensation, sweating was subsequently required to maintain a decreased central temperature during trials of the most effective warming device.

The "paradoxical" decrease in central temperature observed in our unanesthetized volunteers would not occur during recovery from anesthesia. Many recovering patients do not demonstrate thermoregulatory responses despite being markedly hypothermic (presumably because residual anesthetic drugs inhibit regulatory responses).[32] Skin-surface warming would increase mean body temperature in these patients, without causing central hypothermia (the result of active thermoregulatory responses).

Other postoperative patients do respond to hypothermia with peripheral vasoconstriction, shivering, and spontaneous clonic tremor (a synergistic response requiring both hypothermia and residual inhaled anesthesia).[3] Because mean body temperature remains low, these patients would remain relatively vasoconstricted even during skin-surface warming in an effort to increase central temperature. Skin-surface warming has the further advantage in these patients of providing effective treatment for hypothermia-induced shivering.[33,34] Although inhibition of

---

[§] Physiologic mean body temperature (weighted for thermoregulatory responses, rather than heat content) has different coefficients. This equation is only a very rough approximation.

shivering slows rewarming, shivering, not hypothermia *per se*, is most likely associated with postoperative complications.

Area-weighted total heat flux differed markedly from optimal heat flux (detected by a transducer located directly under, and parallel to, radiant heat sources and touching the Bair Hugger® and water blankets). The differences between figures 1 and 2 indicate that the theoretical potential heat transfer from these devices is limited largely by human anatomy, which assures that most skin will not directly contact a water blanket or will be at a suboptimal angle for warming by radiant sources. In contrast, the Bair Hugger® (which has lower potential heat transfer rate per area, compared with water blankets) was most effective overall because it covered a large fraction of the skin surface with warm air.

Heat transfer through insulators (such as the skin and subcutaneous tissues) is proportional to the temperature difference across the insulator. Therefore, it is not surprising that total heat flux correlated well with average skin-surface temperature. Nonetheless, it is usually necessary to measure cutaneous flux directly because heat transfer calculations require other data not easily obtained.

Thermal comfort mediates behavioral modification of heat loss, the most important thermoregulatory response in humans. Thermal comfort is determined by skin-surface temperature, not by tissue heat content, cutaneous heat flux, or central temperature.[27–29] However, comfort produced by a local thermal stimulus depends both on the location of the stimulated skin and the rate of temperature change. For example, facial skin is five times as sensitive as other skin surfaces; furthermore, rapid changes in skin temperature produce approximately five times the response of slow changes.[35] Thus, the relatively poor correlation between thermal flux and comfort may result because flux is a function only of skin temperature and the environment, whereas other factors contribute to thermal comfort.

Because inexpensive, disposable liquid-crystal temperature monitors are now readily available, forehead skin-surface temperature has been promoted as an index of central temperature trends. To be a practical index, it must accurately reflect central temperature during: 1) malignant hyperthermia crises; and 2) mild intraoperative hypothermia. It is unlikely that skin temperature correlates with central temperature during the early phase of malignant hyperthermia because circulating catecholamine concentrations increase to 20 times normal.[36] The resulting cutaneous vasoconstriction may well decrease skin temperature, even while excessive endogenous heat production rapidly increases central temperature.

Skin-surface temperature is determined by diffusion of heat from the central core to the skin, and by loss of heat from the skin to the environment. Diffusion of heat from the core decreases when central temperatures are low, but may also be decreased by cutaneous vasoconstriction (whether thermoregulatory or the result of inadequate vascular volume). Heat loss to the environment may be altered by any of the many factors influencing conduction, convection, and radiation from the skin. The microenvironment surrounding the skin temperature (not central temperature) is thus the dominant factor determining skin-surface temperature.

Temperature changes in the area of the forehead sensor were, by design, unusually large in this study. Nonetheless, the complete lack of correlation between skin and central temperatures clearly indicates the sensitivity of skin temperature to factors other than central temperature changes. Clinicians should, therefore, not assume that changes in skin-surface temperatures reliably indicate central temperature trends unless ambient temperature is demonstrably constant. Even when ambient temperature changes little, forehead temperature correlates poorly with central temperature.[37–39]

We studied volunteers because thermoregulatory vasoconstriction and shivering-like tremor are inhibited by residual anesthetic in some, but not all, postoperative patients. Tremor increases muscular activity and subcutaneous temperature, altering heat flux across the skin by variable and unpredictable amounts. Vasodilated patients will lose more heat to the environment,[4] even without specific warming, which would increase data variability. Finally, a study using patients would require comparison of heat flux between different groups of patients, rather than allowing evaluation of each treatment on each subject. Although central temperature changes would be markedly different in patients, cutaneous heat flux and the increase in mean body temperature produced by each warming device would be similar.

In summary, the circulating-water blanket was the most effective device when only an optimally placed transducer (directly under, and parallel to, the radiant heat sources and touching the warming blankets) was considered. When heat transfer across the entire skin surface was evaluated, the Bair Hugger® set on "medium" (≈38° C) was more effective than each radiant warming device and as effective as the circulating-water blanket. The Bair Hugger® set on "high" (≈43° C) transferred the most heat, enough to increase mean body temperature ≈1.5° C/h in a patient with normal metabolic rate. Skin-surface warming produced the expected thermoregulatory decrease in central temperature in our unanesthetized volunteers. Cutaneous heat flux correlated well with skin-surface temperature, but not with thermal comfort. Forehead skin-surface temperature did not correlate with tympanic membrane temperature and should not be used as an index of central temperature.

References

1. Sessler DI, Rubinstein EH, Eger EI II: Core temperature changes during N_2O fentanyl and halothane/O_2 anesthesia. ANESTHESIOLOGY 67:137–139, 1987
2. Heier T, Caldwell JE, Sessler DI, Miller RD: Mild intraoperative hypothermia increases duration of action and recovery time of vecuronium (abstract). Anesth Analg 70:S153, 1990
3. Sessler DI, Israel D, Pozos RS, Pozos M, Rubinstein EH: Spontaneous post-anesthetic tremor does not resemble thermoregulatory shivering. ANESTHESIOLOGY 68:843–850, 1988
4. Sessler DI, Støen R, Glosten B: Thermoregulatory vasoconstriction significantly decreases heat loss to the environment (abstract). Anesth Analg 70:S362, 1990
5. Bissonnette B, Sessler DI: Passive or active inspired gas humidification increases thermal steady-state temperatures in anesthetized infants. Anesth Analg 69:783–787, 1989
6. Bissonnette B, Sessler DI, LaFlamme P: Passive and active inspired gas humidification in infants and children. ANESTHESIOLOGY 71:381–384, 1989
7. DuBois D, DuBois EF: A formula to estimate the approximate surface area if height and weight be known. Arch Intern Med 17:863–871, 1916
8. Layton RP, Mints Jr WH, Annis JF, Rack MJ, Webb P: Calorimetry with heat flux transducers: Comparison with a suit calorimeter. J Appl Physiol 54:1361–1367, 1983
9. Shanks CA: Mean skin temperature during anaesthesia: An assessment of formulae in the supine surgical patient. Br J Anaesth 47:871–875, 1975
10. Sessler DI, Olofsson CI, Rubinstein EH, Beebe JJ: The thermoregulatory threshold in humans during halothane anesthesia. ANESTHESIOLOGY 68:836–842, 1988
11. Sessler DI, Olofsson CI, Rubinstein EH: The thermoregulatory threshold in humans during nitrous oxide-fentanyl anesthesia. ANESTHESIOLOGY 69:357–364, 1988
12. Støen R, Sessler DI: The thermoregulatory threshold is inversely proportional to isoflurane concentration. ANESTHESIOLOGY 72: 822–827, 1990
13. Burton AC: Human calorimetry: The average temperature of the tissues of the body. J Nutr 9:261–280, 1935
14. Ciofolo MJ, Clergue F, Devilliers C, Ben Ammar M, Viars P: Changes in ventilation, oxygen uptake, and carbon dioxide output during recovery from isoflurane anesthesia. ANESTHESIOLOGY 70:737–741, 1989
15. Macintyre PE, Pavlin EG, Dwersteg JF: Effect of meperidine on oxygen consumption, carbon dioxide production, and respiratory gas exchange in postanesthesia shivering. Anesth Analg 66:751–755, 1987
16. Zwischenberger JB, Kirsh MM, Dechert RE, Arnold DK, Bartlett RH: Suppression of shivering decreases oxygen consumption and improves hemodynamic stability during postoperative rewarming. Ann Thorac Surg 43:428–431, 1987
17. Baumgarten RK: Humidifiers are unjustified in adult anesthesia (letter). Anesth Analg 64:1224–1225, 1985
18. Colin J, Timbal J, Houdas Y, Boutelier C, Guieu JD: Computation of mean body temperature from rectal and skin temperatures. J Appl Physiol 31:484–489, 1971
19. Simon E: Temperature regulation: The spinal cord as a site of extrahypothalamic thermoregulatory functions. Rev Physiol Biochem Pharmacol 71:1–76, 1974
20. Benzinger TH, Pratt AW, Kitzinger C: The thermostatic control of human metabolic heat production. Proc Natl Acad Sci USA 47:730–739, 1961
21. Boulant JA, Hardy JD: The effect of spinal and skin temperatures on the firing rate and thermosensitivity of preoptic neurones. J Physiol (Lond) 240:639–660, 1974
22. Jessen C, Feistkorn G: Some characteristics of core temperature signals in the conscious goat. Am J Physiol 247:R456–R464, 1984
23. Rawson RO, Quick KP: Evidence of deep-body thermoreceptor response to intra-abdominal heating of the ewe. J Appl Physiol 28:813–820, 1970
24. Satinoff E: Neural organization and evolution of thermal regulation in mammals. Science 201:16–22, 1978
25. Brück K: Thermoregulation: Control mechanisms and neural processes, Temperature Regulation and Energy Metabolism in the Newborn. Edited by Sinclair JC. New York, Grune & Stratton, 1978, pp 157–185
26. Stolwijk JAJ, Hardy JD: Partitional calorimetric studies of responses of man to thermal transients. J Appl Physiol 21:967–977, 1966
27. Sessler DI, Ponte J: Shivering during epidural anesthesia. ANESTHESIOLOGY 72:816–821, 1990
28. Glosten B, Sessler DI, Støen R, Faure E, Östman PL: Core temperature changes are not perceived during epidural anesthesia for cesarean section (abstract). ANESTHESIOLOGY 71:A838, 1989
29. Adair ER: Studies on the behavioral regulation of preoptic temperature, Drugs, Biogenic Amines and Body Temperature. Basel, Karger, 1977, pp 84–86
30. Morimoto A, Murakami N, Nakamori T, Watanabe T: Suppression of non-shivering thermogenesis in the rat by heat-seeking behaviour during cold exposure. J Physiol (Lond) 380:541–549, 1986
31. Corbit JD: Voluntary control of hypothalamic temperature. J Comp Physiol Psychol 83:394–411, 1973
32. Sessler DI, Israel DS, Pozos RS, Ruch-Williams V: Postoperative tremor, Thermoregulation: Research and Applications. Edited by Lomax P, Schonbaum E. Basel, Karger, 1989, pp 18–23
33. Murphy MT, Lipton JM, Loughran P, Giesecke Jr AH: Postanesthetic shivering in primates: Inhibition by peripheral heating and by taurine. ANESTHESIOLOGY 63:161–165, 1985
34. Sharkey A, Lipton JM, Murphy MT, Giesecke AH: Inhibition of postanesthetic shivering with radiant heat. ANESTHESIOLOGY 66:249–252, 1987
35. Hensel H: Thermoreception and Temperature Regulation, London, Academic Press, 1981, pp 30–31
36. Sessler DI: Malignant hyperthermia. J Pediatr 109:9–14, 1986
37. Brian JE: Skin temperature monitoring during general anesthesia (abstract). ANESTHESIOLOGY 71:A412, 1989
38. Burgess III G, Cooper JR, Marino RJ, Peuler MJ: Continuous monitoring of skin temperature using a liquid-crystal thermometer during anesthesia. South Med J 71:516–518, 1978
39. Casey W, Broadman L, Rice L, Dailey M: Comparison of liquid crystal skin temperature strip and axillary thermistor probe in measuring core temperature trends during anesthesia in pediatric patients (abstract). ANESTHESIOLOGY 71:A413, 1989