

Body Morphology and the Speed of Cutaneous Rewarming

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Background: Infants and children cool quickly because their surface area (and therefore heat loss) is large compared with their metabolic rate, which is mostly a function of body mass. Rewarming rate is a function of cutaneous heat transfer plus metabolic heat production divided by body mass. Therefore, the authors tested the hypothesis that the rate of forced-air rewarming is inversely related to body size.

Methods: Isoflurane, nitrous oxide, and fentanyl anesthesia were administered to infants, children, and adults scheduled to undergo hypothermic neurosurgery. All fluids were warmed to 37°C and ambient temperature was maintained near 21°C. Patients were covered with a full-body, forced-air cover of the appropriate size. The heater was set to low or ambient temperature to reduce core temperature to 34°C in time for dural opening. Blower temperature was then adjusted to maintain core temperature at 34°C for 1 h. Subsequently, the forced-air heater temperature was set to high ($\approx 43^\circ\text{C}$). Rewarming continued for the duration of surgery and postoperatively until core temperature exceeded 36.5°C. The rewarming rate in individual patients was determined by linear regression.

Results: Rewarming rates were highly linear over time, with correlations coefficients (r^2) averaging 0.98 ± 0.02 . There was a linear relation between rewarming rate ($^\circ\text{C}/\text{h}$) and body surface area (BSA; m^2): Rate ($^\circ\text{C}/\text{h}$) = $-0.59 \cdot \text{BSA} (\text{m}^2) + 1.9$, $r^2 = 0.74$. Halving BSA thus nearly doubled the rewarming rate.

Conclusions: Infants and children rewarm two to three times faster than adults, thus rapidly recovering from accidental or therapeutic hypothermia.

CONSIDERABLE animal data indicates that mild hypothermia (core temperatures near 34°C) provides more protection against cerebral ischemia than available drugs.¹⁻⁴ Evidence is also accumulating that indicates that hypothermia may be beneficial in humans.^{5,6} Consequently, hypothermia is sometimes used during neurosurgery and other procedures in which brain ischemia can be anticipated; many centers use therapeutic hypo-

thermia routinely in adults undergoing neurosurgical procedures.⁷

Infants and children are thought to be particularly susceptible to complications resulting from perioperative hypothermia.⁸ As a result, pediatric patients are often denied the putative benefits of therapeutic hypothermia during neurosurgery. The major reason is that clinicians are concerned that young patients may not rewarm sufficiently quickly and may remain hypothermic postoperatively.

Infants and children cool quickly because their surface area (and therefore heat loss) is large compared with their metabolic rate, which is mostly a function of body mass. Rewarming rate is a function of cutaneous heat transfer plus metabolic heat production divided by body mass. For this reason, it seems likely that infants and children would rewarm faster than adults. Therefore, we tested the hypothesis that the rate of forced-air rewarming is inversely proportional to body size.

Methods

With approval of the Ethics Committee at the University of Texas, Houston Medical School, Houston, Texas, we studied 44 infants, children, and adults scheduled to undergo elective intracranial surgery. All were classified as American Society of Anesthesiologists physical status 1-3. None of the patients were at special risk for bleeding,^{9,10} infection,¹¹ or myocardial ischemia.¹² None had active thyroid disease, history of dysautonomia, Raynaud syndrome, sickle-cell disease, cryoglobulinemia, or malignant hyperthermia.

Protocol

Anesthesia was induced with fentanyl ($2 \mu\text{g}/\text{kg}$), sodium thiopental ($3-4 \text{ mg}/\text{kg}$), and rocuronium ($0.6 \text{ mg}/\text{kg}$) in adults and children with existing intravenous catheters. In contrast, anesthesia was induced by inhalation of sevoflurane and nitrous oxide in infants and children who did not already have an intravenous catheter. An intravenous catheter was inserted, and fentanyl and rocuronium were then administered to the patients. Anesthesia was maintained with isoflurane, 60% nitrous oxide, and fentanyl.

All fluids were warmed to 37°C . Ambient temperature was maintained near 21°C . Patients were covered with a full-body, forced-air cover of the appropriate size (Augustine Medical, Inc., Eden Prairie, MN). The heater was

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Table 1. Morphometric and Demographic Characteristics, and Anesthetic Management

| | < 15 kg | 16–30 kg | 31–90 kg | > 90 kg |
|---|----------------|---------------|---------------|---------------|
| Number of patients | 11 | 11 | 11 | 11 |
| Age (yr) | 1 ± 1 | 5 ± 2 | 26 ± 19 | 44 ± 12 |
| Weight (kg) | 10 ± 5 | 21 ± 4 | 61 ± 22 | 109 ± 15 |
| Height (cm) | 75 ± 24 | 114 ± 17 | 152 ± 12 | 174 ± 11 |
| BSA (m ²) | 0.4 ± 0.2 | 0.8 ± 0.1 | 1.6 ± 0.4 | 2.3 ± 0.2 |
| BSA/mass ratio (m ² /kg) | 0.044 ± 0.007 | 0.038 ± 0.004 | 0.027 ± 0.004 | 0.022 ± 0.001 |
| Sex (M/F) | 9/2 | 7/4 | 3/8 | 7/4 |
| ASA physical status (1/2/3) | 5/5/1 | 5/3/3 | 1/8/2 | 2/7/2 |
| End-tidal [Isoflurane] (%) | 0.9 ± 0.2 | 0.8 ± 0.2 | 0.9 ± 0.3 | 0.8 ± 0.2 |
| End-tidal P _{CO₂} (mmHg) | 29 ± 9 | 32 ± 2 | 32 ± 2 | 32 ± 1 |
| Ambient temperature (°C) | 20.3 ± 0.6 | 20.6 ± 0.2 | 20.4 ± 0.6 | 20.6 ± 0.2 |
| Time to 34°C (h) | 2.5 ± 0.3†§ | 1.6 ± 0.3*†§ | 2.3 ± 0.9†§ | 3.5 ± 0.6*†‡ |
| Cooling rate (°C/h) | 1.7 ± 0.2†§ | 1.6 ± 0.4†§ | 1.2 ± 0.6*†§ | 0.7 ± 0.1*†‡ |
| Cooling correlation coefficient (r ²) | 0.95 ± 0.04†‡§ | 0.98 ± 0.01* | 0.98 ± 0.01* | 0.98 ± 0.01* |
| Core temperature at extubation (°C) | 36.4 ± 0.4§ | 36.6 ± 0.3§ | 36.1 ± 0.8§ | 35 ± 0.4*†‡ |
| Duration of anesthesia (h) | 4.4 ± 0.9§ | 4.3 ± 0.6§ | 5.1 ± 1.1 | 5.8 ± 0.8*† |
| Rewarming rate (°C/h) | 1.8 ± 0.5†‡§ | 1.3 ± 0.2*†§ | 0.9 ± 0.3*†§ | 0.6 ± 0.1*†‡ |
| Rewarming correlation coefficient (r ²) | 0.98 ± 0.02 | 0.98 ± 0.01 | 0.99 ± 0.01 | 0.98 ± 0.02 |

Data are presented as number of patients or mean ± SD. Only values below the dividing line were statistically compared: * significantly different from < 15 kg; † different from 16–30 kg; ‡ different from 31–90 kg; § different from > 90 kg. BSA = body surface area; ASA = American Society of Anesthesiologists.

set to low or ambient temperature with the goal of reducing the patient’s core temperature to 34°C by the time the dura was opened. Blower temperature was then adjusted to maintain core temperature at 34°C for 1 h. Subsequently, the forced-air heater temperature was set to high (≈ 43°C). Rewarming continued for the duration of surgery and postoperatively until core temperature exceeded 36.5°C.

When the surgery was completed, anesthesia was discontinued, and the patients’ tracheas were extubated. However, the patients were kept well-sedated, and shivering was treated with intravenous meperidine.

Measurements

We recorded morphometric and demographic characteristics of all participating patients. All routine anesthetic safety monitors were used; electrocardiographic data, oscillometric blood pressure, end-tidal gas concentrations, and oxyhemoglobin saturation were measured. Core temperature was measured at the tympanic membrane.¹³

Data Analysis

We divided the 44 patients into four equal groups based on body mass. Sex, American Society of Anesthesiologists physical status, anesthetic management, and temperatures in each group were compared with one-way analysis of variance and the Scheffé F test. Results are expressed as mean ± SD. Differences were considered statistically significant when P was less than 0.05.

The rewarming rate in individual patients was determined by linear regression. All temperatures during active rewarming were used in this analysis, including those recorded after extubation. Body surface area

(BSA) in m² was calculated from the formula of Haycock *et al.*¹⁴:

$$BSA (m^2) = 0.025 \cdot [Height (cm)]^{0.3964} \cdot [Mass (kg)]^{0.5378} \quad (1)$$

Results

The four weight groups did not differ significantly with regard to sex, American Society of Anesthesiologists physical status, anesthetic management, or ambient temperature (table 1). Cooling and rewarming rates were both highly linear, with correlations coefficients (r²) averaging 0.97 ± 0.03 and 0.98 ± 0.02, respectively.

There was an inverse relation between core cooling rate and body size. There was similarly an inverse relation between rewarming rate and body weight (fig. 1). There was a linear relation between rewarming rate and BSA: Rate (°C/h) = -0.59 · BSA (m²) + 1.9, r² = 0.74 (fig. 2). Halving BSA thus nearly doubled the rewarming rate. The three highest rewarming rates were in the smallest patients, each weighing only 6 kg. When these three infants were deleted from the analysis, the correlation coefficient increased: Rate (°C/h) = -0.48 · BSA (m²) + 1.7, r² = 0.88.

Discussion

Perioperative heat loss is largely mediated by convection and radiation, with radiation being thought to contribute most.¹⁵ In contrast, conduction and evaporation usually contribute little.^{16,17} Cutaneous heat loss from

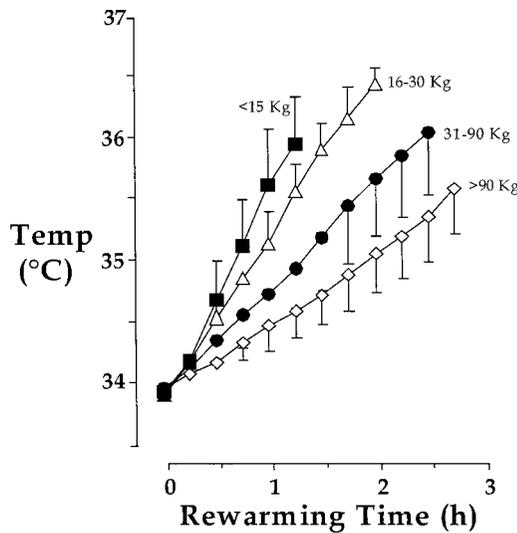


Fig. 1. Core temperature over time was inversely related to patient size. See table 1 for statistical analysis.

undressed adults is 80–100 W at typical operating room temperatures (*i.e.*, 20°C),¹⁸ and is roughly a linear function of surface area.¹⁹ Perioperative cutaneous heat loss in infants remains poorly described. However, it probably exceeds adult values because core temperatures are similar and there is less insulating tissue separating the core from the skin. It is probably also a roughly linear function of surface area over the entire body.

Skin temperature depends on a number of factors including ambient and core temperatures, vasomotor status, and the subjects' previous thermal environment. Nonetheless, skin temperature is usually 2–4°C less than core temperature in the absence of active cutaneous heating. Cutaneous heat transfer during forced-air warming is roughly determined by the difference between skin temperature and the adjacent cover temperature. Because temperature of air entering forced-air covers is externally controlled, usually near 43°C, heat transfer depends largely on skin temperature. Of course, active heating increases skin temperature. However, even prolonged forced-air warming increases mean skin temperature only to 36°C, which is considerably less than the temperature of the air within the cover.

The rewarming rates in three of the smallest patients were obvious outliers, with values that far exceeded those in the other patients. Why these three patients warmed so much faster than the others remains unclear. However, it is unlikely to result from nonshivering thermogenesis because volatile anesthetics peripherally inhibit this response,²⁰ and nonshivering thermogenesis was not detected in infants who were anesthetized with fentanyl and propofol.²¹ Most likely, the rewarming rate was higher than expected in these patients because of subtle factors influencing heat transfer, such as the interaction between the forced-air cover and the patients' skin.

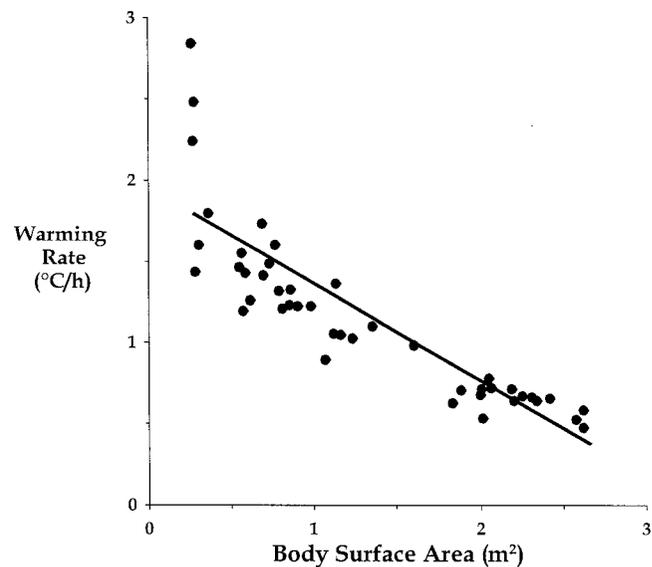


Fig. 2. There was a linear relation between rewarming rate and body surface area (BSA): Rate (°C/h) = $-0.59 \cdot \text{BSA} (\text{m}^2) + 1.9$, $r^2 = 0.74$. The three highest rewarming rates were the smallest patients, each weighing only 6 kg. When these three smallest patients were deleted from the analysis, the regression improved: Rate (°C/h) = $-0.48 \cdot \text{BSA} (\text{m}^2) + 1.7$, $r^2 = 0.88$.

To the extent that hypothermia provides protection against brain ischemia, protection will be a function of brain (*i.e.*, core) temperature. Core temperature is also the single largest factor activating autonomic and behavioral thermoregulatory defenses. Finally, most hypothermia-related complications are probably largely determined by core temperature. Consequently, we evaluated core temperature in this study. Core temperature is also the best single indicator of mean body temperature and body heat content. However, core temperature can differ substantially from mean body temperature. Disparities between core and mean body temperature are likely during rapid thermal perturbations^{22,23} and when thermoregulatory vasomotion isolates core and peripheral tissues^{24–26}; they are especially likely during sudden transitions from surface cooling to surface warming.²⁷

We arbitrarily divided the 44 patients into four groups of 11 based on mass. Potential confounding factors are presented in terms of these groups. However, our primary regression analysis included all patients and was in no way based on a *post hoc* selection.

There was a linear relation between rewarming rate and BSA; halving BSA nearly doubled the rewarming rate. Infants and children thus warmed two to three times faster than adults, thus rapidly recovering from accidental or therapeutic hypothermia.

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