Efficacy of Intraoperative Cooling Methods

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Received from the Department of Anesthesia and Perioperative Care, University of California, San Francisco, California; and Outcomes Research, Department of Anesthesia and General Intensive Care, University of Vienna, Vienna, Austria. Submitted for publication January 22, 1997. Accepted for publication June 12, 1997. Supported by National Institutes of Health grant GM49670, and the Anesthesia Patient Safety (Ermire, PA), Joseph Drown (Los Angeles, CA), Max Kade (New York, NY), Fulbright (Washington, DC), and Erwin-Schrodinger (Vienna, Austria) foundations. Mallinckrodt Anesthesiology Products (St. Louis, MO) donated the thermocouples we used. Cincinnati Sub-Zero. (Cincinnati, OH) donated the circulating-water mattress and cover. Augustine Medical (Eden Prairie, MN) donated the prototype forced-air cooling device. Major corporate funding for the Outcomes Research Laboratory is provided by Augustine Medical, Apotheus Laboratories, and Fairville Medical Optics. The authors do not consult for, accept honoraria from, or own stock or stock options in any anesthesia-related company.

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Abstract

Background: Patients may require perioperative cooling for a variety of reasons including treatment of a malignant hyperthermia crisis and induction of therapeutic hypothermia for neurosurgery. The authors compared heat transfer and core cooling rates with five cooling methods.

Six healthy volunteers were anesthetized with desflurane and nitrous oxide. The cooling methods were 1) circulating water (5 [degree sign] Celsius, full-length mattress and cover), 2) forced air (10 [degree sign] Celsius, full-length cover), 3) gastric lavage (500 ml iced water every 10 min), 4) bladder lavage (300 ml iced Ringer's solution every 10 min), and 5) ice-water immersion. Each method was applied for 40 min or until the volunteers' core temperatures approached 34 [degree sign] Celsius. The volunteers were rewarmed to normothermia between treatments. Core cooling rates were evaluated using linear regression.

The first volunteer developed abdominal cramping and diarrhea after gastric lavage. Consequently, the technique was not again attempted. Bladder lavage increased heat loss 10 [nearly =] 10 W and decreased core temperature 0.8 +/- 0.3 [degree sign] Celsius/h (r² = 0.99 +/- 0.002; means +/- SD). Forced-air and circulating-water cooling comparably increased heat flux, [nearly =] 170 W. Consequently, core cooling rates were similar during the two treatments at 1.7 +/- 0.5 [degree sign] Celsius/h (r² = 0.99 +/- 0.001) and 1.6 +/- 1.1 [degree sign] Celsius/h (r² = 0.98 +/- 0.02), respectively. Immersion in an ice water slurry increased heat loss [nearly =] 600-800 W and decreased core temperature 9.7 +/- 4.4 [degree sign] Celsius/h (r sup 2 = 0.98 +/- 0.01). Immersion cooling was associated with an afterdrop of [nearly =] 2 [degree sign] Celsius.

Conclusions: Bladder lavage provided only trivial cooling and gastric lavage provoked complications. Forced-air and circulating-water cooling transferred relatively little heat but are noninvasive and easy to implement. Forced-air or circulating-water cooling, perhaps combined with intravenous administration of refrigerated fluids, may be sufficient in some patients. When noninvasive methods prove insufficient for rapid cooling, ice-water immersion or peritoneal lavage probably should be the next lines of defense.

Mild hypothermia (1-3 [degree sign] Celsius below normal temperature) provides substantial protection against cerebral ischemia and hypoxemia in many animal species.
As might be expected from these data, core temperatures near 32 °Celsius improve outcome after traumatic brain injury in patients with Glasgow Coma Scores of 5-7. Consequently, many anesthesiologists believe that mild hypothermia is indicated during operations likely to cause cerebral or spinal cord ischemia, such as carotid endarterectomy and neurosurgery. Mild hypothermia also slows triggering of malignant hyperthermia and reduces the severity of the syndrome once triggered in susceptible swine. Core temperatures near 34 °Celsius also appear to facilitate recovery and reduce the risk of death from septic adult respiratory distress syndrome.

Treatment of malignant hyperthermia crises should focus on administration of the specific antidote, dantrolene. However, hyperthermia per se aggravates the syndrome, produces coagulopathy, and may worsen acidosis and electrolyte imbalances. Consequently, most reviews and book chapters on malignant hyperthermia recommend that patients experiencing a crisis be cooled actively. Specific recommendations on how to cool patients, however, tend to be vague and often include statements such as "not only must the patient be cooled externally by water baths, but internal cooling is also necessary. This can be accomplished by intravenous infusions and lavage of the stomach, rectum, and open body cavities with cold solution. Extracorporeal cooling may also be employed."

In practice, it is rarely possible to simultaneously implement several independent cooling strategies, and efforts to do so may detract from other important treatments. Furthermore, some cooling methods are mutually exclusive (i.e., circulating water and water immersion), and others have substantial intrinsic dangers. It would thus be helpful to provide clinicians with specific cooling recommendations, based on the relative efficacy of available methods. Therefore, we compared heat transfer and core cooling rates with five different cooling methods: circulating water, forced air, gastric lavage, bladder lavage, and ice-water immersion.

Methods

With approval from the Committee on Human Research at the University of California in San Francisco and informed consent from volunteers, we studied six healthy men or women, each on 2 days. Morphometric characteristics included age, 27 +/- 3 yr; weight, 75 +/- 11 kg; height, 176 +/- 12 cm; and body fat, 20 +/- 2%.

Anesthetic Management

Studies started at approximately 9:00 A.M., and volunteers fasted 8 h before coming to the laboratory. The room was maintained near 23 °Celsius and had a relative humidity near 45% (model HX93 humidity transmitter; Omega Engineering,
Stamford, CT). The volunteers were minimally clothed during the protocol and rested supine on a standard operating room table. An intravenous catheter was inserted, and nearly 10 ml/kg lactated Ringer's solution warmed to 37 [degree sign] Celsius was infused immediately before induction of anesthesia. Subsequently, warmed fluid was infused at a rate of nearly 5 ml [center dot] kg sup -1 [center dot] h sup -1. To minimize redistribution hypothermia, the volunteers were prewarmed with forced air for 30 min before induction of anesthesia.

Anesthesia was induced, without any premedication, by administering 3-4 mg/kg propofol and nitrous oxide. Vecuronium bromide (10 mg) was administered intravenously and the trachea was intubated. Muscle relaxation was subsequently maintained with an infusion of vecuronium adjusted to maintain 0-1 twitches in response to supramaximal train-of-four electric stimulation of the ulnar nerve at the wrist. Ventilation was controlled at a rate and volume sufficient to maintain end-tidal partial pressure of carbon dioxide near 35 mmHg. Fresh gas flow was maintained near 2 l/min; heat- and moisture-exchanging filters were not used. Anesthesia was maintained with desflurane, at 3-4% end-tidal concentration, in 60% nitrous oxide in oxygen. When the study period was complete, neuromuscular block was antagonized, anesthesia discontinued, and the trachea extubated.

Thermal Management

After induction of general anesthesia, two or three of the cooling methods listed below were instituted on each study day. Treatment order was semirandom and constrained by the following rules: (1) cutaneous and core cooling methods were alternated, and (2) volunteers were immersed in ice-water at the end of a study day.

1. Skin-surface cooling with a full-length cover attached to a prototype forced-air cooler (Augustine Medical, Eden Prairie, MN). This device provides 1,000 l/min air at 10 [degree sign] Celsius. The cover was positioned directly on the volunteers' skin, and the entire body below the neck was covered.

2. Gastric lavage, using sterile water instilled via an 16-French, double-lumen orogastric tube. The fluid was cooled by passing it through a cardiopulmonary bypass heat exchanger immersed in an ice-and-water slurry. Sterile water ([nearly =] 500 ml) was allowed to flow into the stomach under gravity, and was then aspirated 5 min later. Each cycle lasted about 10 min.

3. Skin-surface cooling with a circulating-water mattress (below) and blanket (above) (Cincinnati Sub-Zero, Cincinnati, OH). The water temperature was set to 5 [degree sign] Celsius. The mattress and blanket were positioned directly on the volunteers' skin, and the entire body below the neck was covered.
4. Bladder lavage using Ringer's solution instilled via a 16-French, double-lumen urethral catheter. The fluid was cooled by passing it through a cardiopulmonary bypass heat exchanger immersed in an ice-and-water slurry. Sterile fluid ([nearly =] 300 ml) was allowed to flow into the bladder under gravity and was then aspirated 5 min later. Each cycle lasted [nearly =] 10 min.

5. Cutaneous cooling induced by partial immersion in iced water. A plasticized canvas sheet was positioned under the volunteer, with the edges suspended from four sets of gynecologic stirrups attached to the operating table frame. Approximately 50 l crushed ice was poured into the sheet and sufficient water was pumped in to cover the volunteers from the neck down. Cooling was stopped by lowering one corner of the sheet, thus allowing the ice-and-water slurry to drain into a large basin.

The circulating-water and forced-air devices were pre-cooled before each application for 5 min. Each type of cooling was administered for 40 min, or until the core temperature reached 34 [degree sign] Celsius. Between each cooling trial, volunteers were rewarmed with forced air to a core temperature exceeding 36 [degree sign] Celsius. Then they were covered with two cotton blankets before starting the subsequent cooling trial. These blankets were removed when surface cooling methods were tested but left in place when internal cooling techniques were evaluated.

**Measurements**

Heart rate and oxyhemoglobin saturation ($S_pO_2$) were measured continuously using pulse oximetry, and blood pressure was determined oscillometrically at 5-min intervals. Expiratory carbon dioxide concentrations were measured from a Capnomac Ultima monitor (Datex, Helsinki, Finland). Area-weighted heat flux from 15 skin-surface sites [15] was measured using thermal flux transducers (Concept Engineering, Old Saybrook, CT). [18] We defined flux as positive when heat traversed skin to the environment.

Core temperature was recorded from the tympanic membrane using Mon-a-Therm thermocouples (Mallinckrodt Anesthesiology Products, St. Louis, MO). The aural probes were inserted by the volunteers until they felt the thermocouple touch the tympanic membrane; appropriate placement was confirmed when volunteers easily detected a gentle rubbing of the attached wire. The aural canal was occluded with cotton, the probe securely taped in place, and a gauze bandage positioned over the external ear. The volume and temperature of fluid instilled into and removed from the bladder and stomach were recorded. Temperatures were recorded at 5-min intervals from thermocouples connected to calibrated Iso-Thermex thermometers (Columbus Instruments, Corp., Columbus, OH) having an accuracy of 0.1 [degree sign] Celsius and a precision of 0.01 [degree sign] Celsius.

**Data Analysis**
Environmental conditions, end-tidal desflurane concentrations, and initial core temperatures and heat flux on each study day were averaged for each volunteer, and the resulting values were then averaged among volunteers. Results for each study day were compared using repeated-measures analysis of variance and Scheffe's F tests.

Heat transfer during surface cooling was determined from the cutaneous thermal flux transducers and compared to pretreatment values. During bladder and gastric cooling, the rate of heat transfer was determined from lavage volume, temperature of the injected and recovered fluid, and cycle time using the formula \( \text{Equation 1} \) where flux is heat transfer in watts, Delta T is the temperature difference in degrees Celsius between instilled and aspirated fluid, V is lavage volume in liters, S is the specific heat of water (1 kcal [center dot] [degree sign] Celsius sup -1 [center dot] L sup -1), and t is time in hours. When we could not remove all infused fluid, fluid remaining in the body was assumed to have equilibrated to core temperature. This equation evaluates only the specific effect of body cavity lavage. Heat flux, in all cases, was thus considered to be only the incremental effect of treatment.

\[
\text{Flux} = \Delta T \cdot V \cdot S (1.16 \text{ W} \cdot \text{kcal}^{-1} \cdot \text{L}^{-1})/t
\]

\( \text{Equation 1} \)

Heat flux and core temperatures resulting from application of each device, at each time, were compared with repeated-measures analysis of variance and Scheffe's F tests. The rates of core temperature decrease were determined for each device in each volunteer using linear regression over the period from 10 elapsed min until the end of active cooling. These rates were compared among devices with repeated-measures analysis of variance and Scheffe's F tests. Data are presented as mean +/- SD; \( P < 0.05 \) was considered significant.

**Results**

Gastric lavage in the first volunteer was notable because we were able to aspirate only about 30% of the administered fluid. During postanesthetic recovery, prolonged abdominal cramping and diarrhea developed. Consequently, gastric lavage was not attempted in the other volunteers. Her heat loss during lavage was 30 W and her core temperature decreased 1.5 [degree sign] Celsius during the 40 min of the study. Ambient temperatures, relative humidity, end-tidal desflurane concentrations, initial cutaneous thermal flux, and initial core temperatures were comparable during the other treatments (Table 1).

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Within 40 min of bladder lavage, we performed four cooling cycles. Temperature of the
Infused saline was 6 +/- 2 °Celsius; temperature of recovered saline was 21 +/- 2 °Celsius; exchange volume was [nearly =] 300 ml. Consequently, bladder lavage increased heat loss [nearly =] 10 W and decreased core temperature 0.8 +/- 0.3 °Celsius/h ($r^2 = 0.99 +/- 0.002$). Forced-air and circulating-water cooling comparably increased heat flux [nearly =] 170 W. Consequently, core cooling rates were similar during the two treatments: 1.7 +/- 0.5 °Celsius/h ($r^2 = 0.99 +/- 0.001$) and 1.6 +/- 1.1 °Celsius/h ($r^2 = 0.98 +/- 0.02$), respectively.

Immersion in an ice-and-water slurry proved by far the most effective cooling method. Immersion increased cutaneous heat flux [nearly =] 800 W after 10 min and flux remained [nearly =] 600 W after 20 min. Core temperature consequently decreased 9.7 +/- 4.4 °Celsius/h ($r^2 = 0.98 +/- 0.01$). Because core temperature rapidly approached 34 °Celsius, immersion was terminated after just 20 min. Despite complete drying of the anterior skin and aggressive postimmersion forced-air warming, a core-temperature after-drop of nearly 2 °Celsius was observed. Figure 1 summarizes treatment-induced changes in heat flux, and Figure 2 shows the resulting effects on core temperature.

**Discussion**

Gastric lavage provided moderate core cooling ([nearly =] 30 W). This amount is unlikely to cool the core quickly enough to be considered therapeutic or to compensate for the large quantities of metabolic heat released during malignant hyperthermia crises. The technique failed, in any case, because we could not aspirate much of the injected fluid. As a result, considerable diarrhea and gastrointestinal discomfort developed in the
single volunteer in whom we attempted the procedure. The method has also proved unsatisfactory during rewarming from accidental hypothermia. Thus we cannot recommend gastric lavage as either an effective or safe cooling method.

The other method of internal cooling we attempted—bladder lavage—failed to transfer an adequate amount of heat. Bladder lavage increased heat loss by only about 10 W, presumably because flux was restricted by the bladder's small surface area and relatively low blood flow. Bladder cooling provided the lowest heat transfer of any method we tested and would be of little value during a malignant hyperthermia crisis. Thus we also cannot recommend bladder lavage for this purpose. We did not evaluate rectal lavage. It is likely, however, that this method would prove considerably more effective than bladder lavage because the colon presents a far larger surface area than the bladder and is better perfused. To our knowledge, heat transfer during rectal lavage has never been quantified.

Peritoneal lavage has been used extensively to treat accidental hypothermia and typically increases core temperature \(\text{[nearly =]}\ 5-10 \ [\degree \text{Celsius/h}]\). Core cooling rates have not been evaluated specifically during peritoneal lavage but should be even greater than warming rates because larger body-to-fluid temperature differences can be supported. A disadvantage of peritoneal lavage is that the procedure is invasive. The required level of skill, however, should be readily available in most operating suites.

Administration of ice-cold intravenous fluid also directly cools core tissues and has been used for this purpose in physiologic studies and in the treatment of heat stroke. Each liter of fluid given at 4 \[\degree \text{Celsius}\] decreases mean body temperature \(\text{[nearly =]}\ 0.5 \ [\degree \text{Celsius}]\). The method is obviously restricted by the volume that can be administered without overloading the cardiovascular system. However, administration of a reasonable volume, such as 4 l during a 1-h period, corresponds to a heat transfer rate of 150 W (from \text{Equation 1}).

The final commonly recommended method of internal cooling is partial cardiopulmonary bypass. Before dantrolene was available, patients were adequately cooled during malignant hyperthermia crises with cardiopulmonary bypass. Since intravenous dantrolene became available in 1979, however, such aggressive cooling has rarely been required. Unlike peritoneal lavage, cardiopulmonary bypass is extremely invasive and requires considerable skill with special equipment. Even in hospitals where the technique is available, cardiopulmonary bypass will certainly require far longer to initiate than other invasive core cooling methods such as peritoneal lavage.

Forced-air and circulating-water surface cooling has the advantage of being risk free and easy to implement rapidly. As expected from previous reports, forced air and circulating water transferred comparable amounts of heat \(\text{[nearly =]}\ 170 \ W\) and consequently decreased core temperature \(\text{[nearly =]}\ 1.6 \ [\degree \text{Celsius/h}]\).
Although this level of cooling facilitates implementation of therapeutic hypothermia during neurosurgery, \[23,24\] it is unlikely to be sufficient during malignant hyperthermia crises.

Immersion in an ice-and-water slurry increased heat loss to \[\text{nearly} \approx 600-800\text{ W}\] and decreased core temperature at a rate of \[\text{nearly} \approx 9.7\text{ }^\circ\text{C/h}\]. These values are consistent with physiologic investigations in which volunteers were immersed in stirred water at \[\text{nearly} \approx 8\text{ }^\circ\text{C}\]. \[24,25\] Water immersion was by far the most effective treatment we tested and cooled the core about six times as fast as forced air or circulating water.

Although water immersion is noninvasive, it is hardly trivial to implement. First, a strong, water-impermeable sheet must be positioned beneath the patient. The sheet must then be mechanically suspended because sufficient ice and water to cover a patient can easily weigh more than 100 kg. Finally, sufficient help must be available to rapidly fill the sheet with ice and water. The method is more difficult than might be thought; even under controlled conditions, some "flooding" of the floor seems inevitable. Considerable preparation will be required if water immersion is going to be implemented sufficiently rapidly during an unanticipated malignant hyperthermia crisis.

An additional limitation of water immersion is that cardiopulmonary resuscitation would be difficult. Even after the fluid is drained (a process requiring at least a few minutes), electric defibrillation or cardioversion would be unsafe. A final difficulty with water immersion is that core cooling continues even after rewarming has begun. This continued decrease in core temperature is known as afterdrop. Both conduction \[26\] and convection \[27\] contribute to afterdrop, the magnitude of each being determined by the circumstances of cooling and rewarming. \[28\]

We did not evaluate thermoregulatory vasoconstriction, but, judging from previous studies, \[29,30\] we can assume that the volunteers were vasoconstricted well before active cooling was stopped at \[\text{nearly} \approx 34\text{ }^\circ\text{C}\] and remained constricted as core temperature continued to decrease. Under the condition of our study, afterdrop is thus likely to have resulted largely from conduction rather than convection. The magnitude of the afterdrop when cold water is removed is typically \[\text{nearly} \approx 0.6\text{ }^\circ\text{C}\], which is only one third of the amount we observed. The large afterdrop in our volunteers likely resulted from anesthesia and muscle relaxation, which prevented the normal hypothermia-induced increase in endogenous heat production.

A limitation of our protocol is that our volunteers presumably had nearly normal plasma catecholamine concentrations, although values 20 or 30 times greater are typical during
malignant hyperthermia crises. Elevated catecholamine concentrations provoke intense vasoconstriction, which will restrict cutaneous-to-core heat transfer. Nonetheless, heat transfer during ice-water immersion is so great that conduction, rather than convection, is surely the most important mechanism. To the extent that conductive transfer predominates, vasoconstriction will only minimally impede cooling during immersion. Similarly, metabolic rates in our volunteers were presumably near normal, although heat production is markedly increased during malignant hyperthermia crises.

All of our volunteers were of relatively normal body habitus. Surface cooling techniques will be relatively less effective in obese persons, and they will be relatively more effective in thin ones. Our purpose was to evaluate clinically available cooling methods. Thus we used each device at its coldest available setting. A natural consequence of this approach is that some of the devices were tested at different temperatures (i.e., circulating water and forced air). These temperatures are, however, those that are likely to be available to clinicians during malignant hyperthermia crises.

In summary, bladder lavage provided only trivial cooling and gastric lavage provoked complications. Neither would thus appear to have any role in the induction of therapeutic hypothermia or management of malignant hyperthermia crises. Administration of refrigerated intravenous fluid is easy to implement and only requires that the operating suite maintain an adequate supply of cooled saline. Forced-air and circulating-water cooling transferred relatively little heat but are noninvasive and easy to implement. The combination of cooled intravenous fluids and forced-air or circulating-water cooling may be sufficient in some patients, in which case more difficult and invasive methods can be avoided. When noninvasive methods prove insufficient, however, peritoneal lavage or ice-water immersion should probably be the next line of defense. It is unlikely that both would be required, so clinicians can chose whichever they believe to be most convenient and quickest in their setting.

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