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Heating and Cooling Rates With an Esophageal Heat Exchange System

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BACKGROUND: The Esophageal Cooling Device circulates warm or cool water through an esophageal heat exchanger, but warming and cooling efficacy in patients remains unknown. We therefore determined heat exchange rates during warming and cooling.

METHODS: Nineteen patients completed the trial. All had general endotracheal anesthesia for nonthoracic surgery. Intraoperative heat transfer was measured during cooling (exchanger fluid at 7°C) and warming (fluid at 42°C). Each was evaluated for 30 minutes, with the initial condition determined randomly, starting at least 40 minutes after induction of anesthesia. Heat transfer rate was estimated from fluid flow through the esophageal heat exchanger and inflow and outflow temperatures. Core temperature was estimated from a zero-heat-flux thermometer positioned on the forehead.

RESULTS: Mean heat transfer rate during warming was 18 (95% confidence interval, 16–20) W, which increased core temperature at a rate of 0.5°C/h ± 0.6°C/h (mean ± standard deviation). During cooling, mean heat transfer rate was −53 (−59 to −48) W, which decreased core temperature at a rate of 0.9°C/h ± 0.9°C/h.

CONCLUSIONS: Esophageal warming transferred 18 W which is considerably less than the 80 W reported with lower or upper body forced-air covers. However, esophageal warming can be used to supplement surface warming or provide warming in cases not amenable to surface warming. Esophageal cooling transferred more than twice as much heat as warming, consequent to the much larger difference between core and circulating fluid temperature with cooling (29°C) than warming (6°C). Esophageal cooling extracts less heat than endovascular catheters but can be used to supplement catheter-based cooling or possibly replace them in appropriate patients. (Anesth Analg 2018;126:1190–5)

KEY POINTS

- **Question:** How much heat can be transferred through an esophageal heat exchanger?
- **Findings:** Mean heat transfer during warming was 18 (95% confidence interval, 16–20) W; mean heat transfer during cooling was −53 (−59 to −48) W.
- **Meaning:** Esophageal heating and cooling can supplement other heat exchange systems.

Perioperative hypothermia causes various complications including coagulopathy and increased transfusion requirement,[1] surgical site infection,[2] delayed drug metabolism and prolonged recovery,[3,4] and thermal discomfort.[4] Consequently, it is now standard of care to keep surgical patients normothermic.[5] Therapeutic hypothermia or targeted temperature management is occasionally used in critical care patients, with the most common thermal challenge in intensive care units being treatment of fever[6] that is unresponsive to pharmacologic interventions.[7]

Available thermal management systems provide an array of efficacy, safety, and cost options.[8] By far, the most commonly used intraoperative system is forced air, presumably because forced-air warming is effective, inexpensive, and remarkably safe.[9,10] Resistive heating systems are a comparably effective alternative.[11,12] Systems based on circulating water have the advantage of cooling as well as heating, and can thus be used for the treatment of fever in critical care unit.[13] Some are quite efficient.[14] Heat transfer with all these systems depends critically on available surface area. Short of cardiopulmonary bypass and perhaps peritoneal lavage, endovascular heat exchange catheters are the fastest way to warm and cool patients,[15,16] although the catheters are expensive and invasive.

Heat exchange through the esophagus dates at least to 1993,[17] and the method is attractive because esophageal heating or cooling might supplement other systems that exchange heat through the skin surface. Heat transfer through the esophagus depends on various factors including temperature of the heat exchange fluid, fluid-flow rate, thickness and thermal insulation of the exchange element, and, most importantly, the ability of the esophagus to absorb or relinquish heat—which in turn will be a function of tissue insulation and blood flow. Because factors affecting esophageal heat exchange are not easily modeled using engineering analyses, we experimentally determined heat transfer to the esophagus. Our primary goal was thus to determine heat transfer rates during warming and cooling

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This study was registered at ClinicalTrials.gov.

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with an esophageal heat exchanging system. Secondarily, we sought to measure the influence of this device on the temperature of patients having noncardiac surgery.

METHODS

Our study was conducted with Institutional Review Board approval (16–124) and was registered at ClinicalTrials.gov (NCT02743884, Principal Investigator, D.I.S.). Per protocol, we initially enrolled 3 pilot patients whose results were not included in the analysis. We enrolled 22 adults who had noncardiac surgery with general anesthesia at the Cleveland Clinic Main Campus that was expected to last at least 2 hours. Each was 18–80 years old, had a body mass index <38 kg/m^2, and was American Society of Anesthesiologists physical status I–III. We excluded hemodynamically unstable patients including those who had labile hypertension, sustained tachycardia, peripheral vascular disease, sepsis, and anticipated use of intraoperative vasodilators and/or vasoconstrictors. Patients with esophageal pathology were also excluded. All patients provided written informed consent and received standard American Society of Anesthesiologists monitoring.

The esophageal heat exchanging orogastric tube we tested was the Esophageal Cooling Device (Advanced Cooling Therapy, Chicago, IL), which is a class II US Food and Drug Administration-cleared system. It is a single-use triple-lumen silicone system inserted into the esophagus through the mouth. The external ports are connected to a Gaymar Medi-Therm III (Stryker Corp, Kalamazoo, MI) circulating water system, while a third, central lumen allows gastric decompression and drainage (Figure 1).

Figure 1. The heat exchanging tube. The outer tubes are connected to a Gaymar Medi-Therm III circulating water system.

General anesthesia was induced per routine, with propofol, opioid, and a muscle relaxant. The trachea was intubated and anesthesia was maintained with sevoflurane. The esophageal heat exchange system was inserted through the mouth to a length equal to the distance from the mouth to the ear and then to the xiphoid process, and its position was confirmed by auscultating over the stomach. The central port was connected to low intermittent suction to keep the stomach decompressed, and the heat exchange ports were connected to the Gaymar Medi-Therm III external heat exchanger.

Each patient was warmed and cooled, each for 30 minutes, in random order, with 30 minutes elapsing between each test. Randomization occurred within 15 minutes of anesthetic intubation via a secure web-based system based on computer-generated codes with random permuted blocks. Allocation was thus concealed for as long as practical. Blinding of outcome assessor was not possible and unnecessary since the temperature outcomes were purely objective.

The initial cooling or warming test started at least 40 minutes after anesthetic induction. During cooling the unit's fluid temperature was set to 7°C, and during heating it was set to 42°C. A bypass system was used so that patients were exposed to full cooling and full warming for exactly 30 minutes each. All patients were warmed with an upper or lower body forced-air cover set to "high" (≈43°C), and intravenous fluids were warmed to body temperature. Operating room temperature, depth of anesthesia, and mean arterial pressure were kept as constant as practical during the study period. The Esophageal Cooling Device was removed at the end of surgery.

Measurements

Patients demographic and morphometric characteristics were obtained from electronic medical records. Esophageal and nasopharyngeal temperatures, which are usually the best sites during general anesthesia, are likely to be artifactually warmed or cooled by the test heat exchange system. We therefore estimated core temperature with a zero-heat-flux forehead monitor (Bair Hugger Thermometer, formerly SpotOn [3M; St. Paul, MN]).[18] Ambient and core temperatures, end-tidal sevoflurane, mean arterial pressure, and heart rate were measured at 10-minute intervals during warming and cooling.

During each heating and cooling period, temperature of water flowing into and out of the esophageal heat exchanger was measured at 1-second intervals using a commercial ultra-precise thermistor (P-M-1/10–1/4-6-0-P-15; Omega, Norwalk, CT) accurate to ±0.04°C. Water flow through the heat exchanger was determined at 1-second intervals by a paddle-wheel flowmeter (Omega DFLR1012-D) accurate to ±0.05 mL/min and having a repeatability of ±0.2%.

Postoperatively, patients were evaluated for adverse events including gastric distention, sore throat and other evidence of esophageal injury, cardiac arrhythmias, dysphagia, and odynophagia in the postanesthesia care unit and the morning after surgery.

Our a priori primary outcome was average heat transfer rate during the esophageal cooling and warming periods. Heat transfer rate, $\dot{Q}$ in watts, was defined as the difference between inflow and outflow temperatures multiplied by flow and the specific heat of water using the following formula:

$$\dot{Q} = \Delta T\,(°\mathrm{C}) \times C_p\left(\frac{\mathrm{cal}}{°\mathrm{Cg}}\right) \times \dot{V}\left(\frac{\mathrm{mL}}{\mathrm{min}}\right) \times \rho\left(\frac{\mathrm{g}}{\mathrm{mL}}\right) \times \left(\frac{\mathrm{kcal}}{1000\,\mathrm{cal}}\right) \times \left(\frac{60\,\mathrm{min}}{\mathrm{h}}\right) \times \left(\frac{1.16\,\mathrm{W\,h}}{\mathrm{kcal}}\right)$$

where
$\dot{Q}$ = heat transfer (watts)
ΔT = temperature change (°C)
C_p = specific heat (cal/°C g)
$\dot{V}$ = volume flow rate (mL/min)
ρ = density (g/mL)
1.16 W = 1 kcal/h

and C_p was considered to be 1.0 kcal·kg^{-1}·°C^{-1}. Heat transfer rate was calculated second by second during 30 minutes of warming or cooling for each patient based on measurements of inflow and outflow water temperatures and water flow rate (mL/min). The start of each warming and cooling period was considered elapsed time zero. For each patient, we estimated heat transfer during warming and cooling as the median of the second-by-second measurements between 5–10, 15–20, and 25–30 elapsed minutes and over each full 30-minute period. The medians were used to protect the estimates from inflating by outliers.

Our secondary outcome was the change in core temperature[18] from the beginning to the end of each 30-minute-long warming and cooling period.

Statistical Analysis

Initially, we summarized each patient's demographic and morphometric characteristics using standard univariable summary measures, presented as means ± standard deviations (SDs) or N (%), as appropriate.

Mean heat transfer rate and 95% confidence interval (CI), our primary outcomes, were estimated over the entire 30-minute period for both cooling and warming cycles assuming normal distribution. The distribution of heat transfer values during cooling and warming was summarized with boxplots between 5–10, 15–20, and 25–30 elapsed minutes for warming and cooling periods. Changes in core temperature from the beginning to the end of each 30-minute heat exchange period were reported as means and SDs. Two post hoc paired *t* tests were used to compare before and after core temperatures to assess any statistically significant changes for the 30-minute cooling and warming periods.

SAS 9.4 statistical software (SAS Institute, Cary, NC) and R statistical software version 2.15.2 for 64-bit Unix operating system (The R Foundation for Statistical Computing, Vienna, Austria) were used for all analyses.

Sample Size Consideration

We calculated sample size of the study aiming for reasonable precision in estimating mean heat transfer rate (precision is described in terms of CI width). Specifically, given the heat transfer SD of 12 W during cooling, the obtained 19 patients were enough for half-width 95% CIs of 7 W or less. CI width was estimated using the exact method assuming normal distribution of the data.

RESULTS

A total of 25 Cleveland Clinic patients consented to participate in the study, and after excluding 3 pilot patients and 3 incomplete patients, 19 patients were included in the final analysis (Figure 2). We had incomplete outcomes for 3 patients because of surgery ending early in the first, inability to pass the esophageal tube in the second, and a malfunction of the data logger in the third. None of their data were included in our analysis.

During anesthesia, there was no clinically important difference in end-tidal sevoflurane, mean arterial pressure, and heart rates during the warming and cooling periods (results not presented).

Demographic, morphometric, and preoperative characteristics are reported in the Table. Typical differences between fluid flowing into and out of the esophagus were 0.4°C, and flow was about 1 L/min.

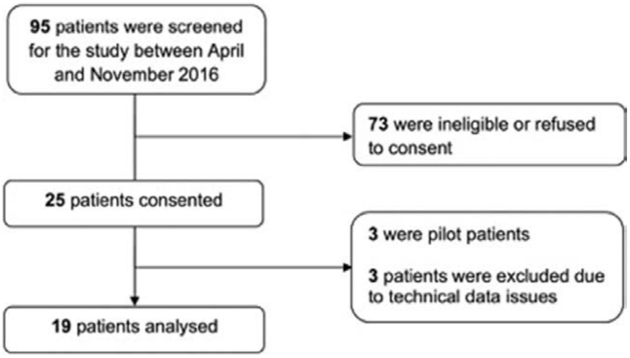


Figure 2. Study flow diagram.

Table. Summary of Patients' Demographic, Morphometric, and Preoperative Characteristics Given as "Mean ± Standard Deviation" or N (%) (N = 19 patients)

Factor	N = 19
Age (y)	52 ± 14
Sex, female	8 (42)
Weight (kg)	87 ± 17
Height (cm)	173 ± 12
Body mass index (kg/m^2)	29 ± 5
Type of surgery	
Breast	2 (11)
Gastrointestinal/genitourinary	16 (84)
Shoulder	1 (5)
Preoperative oral temperature (°C)	36 ± 0
Depth of the heat exchange tube (cm)	54 ± 7

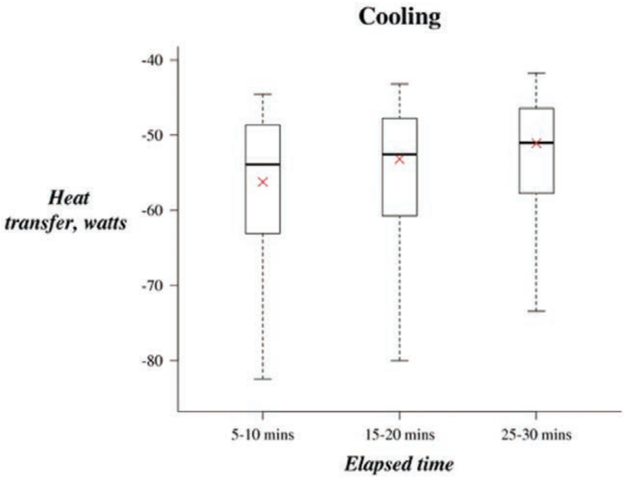


Figure 3. Heat transfer during cooling. Mean heat transfer over 30 min was −53 (95% confidence interval, −59 to −48) W. The middle, upper, and lower edges of the boxplot indicate the 50th, 75th, and 25th percentiles, respectively. The ends of the vertical lines indicate 1.5 times the interquartile range. The cross inside the boxplot is the mean.

The primary results of the study are presented in Figures 3 and 4. During both warming and cooling, heat transfer decreased slightly over time. Mean heat transfer rate over 30 minutes of cooling was −53 (95% CI, −59 to −48) W and 18 (95% CI, 16–20) W during warming.

Initial core temperature during warming averaged 35.5°C ± 0.5°C (SD), increasing to 35.8°C ± 0.6°C over 30 minutes. The mean warming rate was thus 0.5°C/h ±

0.6°C/h, which was a significant increase (paired *t* test *P* value = .001). During cooling, initial core temperature was 35.7°C ± 0.6°C, decreasing to 35.3°C ± 0.6°C over 30 minutes. The mean cooling rate was thus 0.9°C/h ± 0.9°C/h, which was statistically significant ($P < .001$). Raw temperatures are shown in Figure 5.

DISCUSSION

Esophageal heat exchange, our primary outcome, is independent from environmental temperature, external heating, heat loss from within surgical incision, and fluid-induced cooling. Instead, it was directly measured and only a function of water temperature, water flow, and insulation provided by the plastic catheter and esophageal tissues. Our results are thus broadly applicable and will be similar over a wide range of patient, surgical, and environmental conditions.

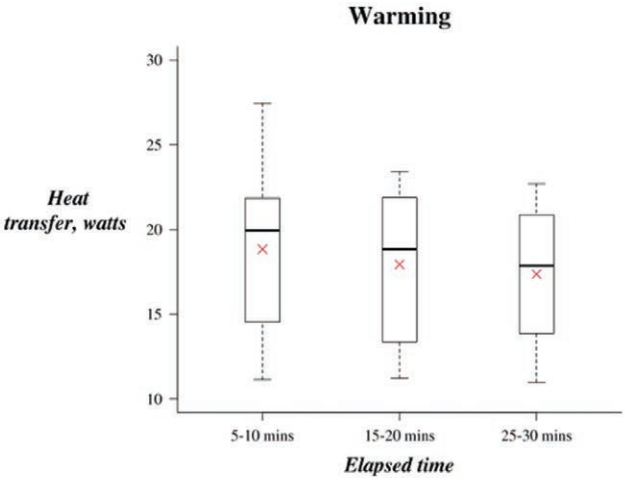


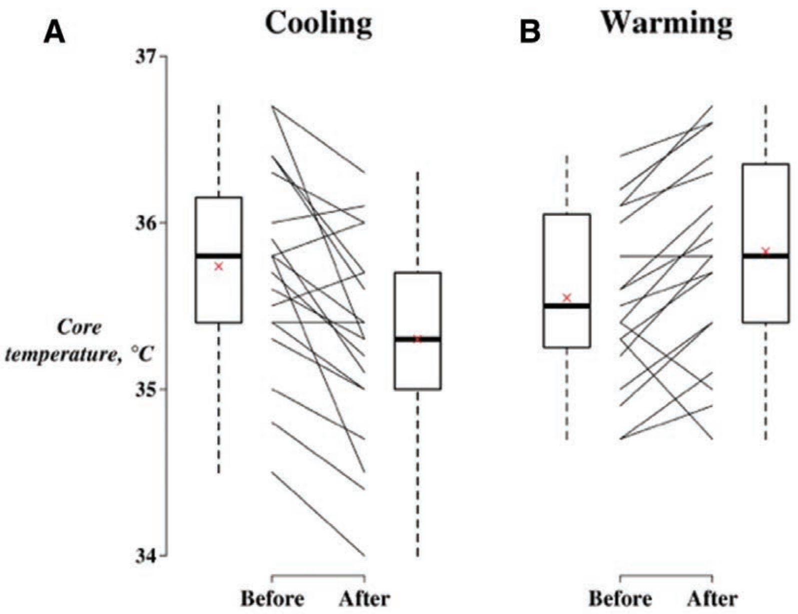
Figure 4. Heat transfer during warming. Mean heat transfer over 30 min was 18 (95% confidence interval, 16–20) W. The middle, upper, and lower edges of the boxplot indicate the 50th, 75th, and 25th percentiles, respectively. The ends of the vertical lines indicate 1.5 times the interquartile range. The cross inside the boxplot is the mean.

Mean heat transfer rate during esophageal warming was 18 W. For reference, 67 W sustained for 1 hour will increase mean body temperature 1°C in a 70-kg adult who is otherwise at thermal steady state. Eighteen watts thus corresponds to about a quarter-of-a-°C per hour increase in mean body temperature. This rate is similar to a Cool Line endovascular catheter (Omega, Norwalk, CT) and about half the rate of the newer Solex 7 endovascular catheter (Zoll, Chelmsford, MA). By comparison, full-body Bair Hugger (3M) forced-air heating systems transfer about 170 W.[8,19] However, full-body covers cannot be used for most surgical procedures. Upper or lower body covers are thus nearly always used. Each transfers about half as much heat as a full cover, perhaps 80 W assuming they can be fully deployed. Esophageal heating thus transfers roughly one-quarter as much heat as forced air.

Esophageal heating might be sufficient to keep some patients normothermic during surgery, but by itself it will probably prove insufficient in many cases. An attractive feature of the system is that it can be used in addition to surface warming, or deployed in cases where surface cooling is impractical. Esophageal warming can thus be added to forced air in patients who are or are likely to become hypothermic despite cutaneous warming.

Esophageal cooling transferred more than twice as much heat as warming (−53 vs 18 W). Better efficacy was a natural consequence of the much larger difference between core and circulating fluid temperature with cooling (36°C − 7°C = 29°C) than warming (42°C − 36°C = 6°C). Esophageal cooling is thus more likely to be clinically practical than esophageal warming and might, for example, be used for fever control[6] or induction of therapeutic hypothermia—although there seems to be little current indication for deliberate hypothermia.[20–23] Heat transfer during cooling was considerably less than reported with Cool Line (74 W) or Solex 7 (144 W) endovascular catheters. But as with forced-air warming,

Figure 5. Raw temperature. Each line represents individual temperature change for 19 patients. The middle, upper, and lower edges of the boxplot indicate the 50th, 75th, and 25th percentiles, respectively. The ends of the vertical lines indicate 1.5 times the interquartile range. The cross inside the boxplot indicates a mean temperature. A, Two boxplots of core temperature estimated from a zero-heat-flux thermometer on the forehead before and after 30-min cooling with Esophageal Cooling Device with a middle plot of individual patients temperature change. During cooling, initial core temperature was 35.7°C ± 0.6°C, decreasing to 35.3°C ± 0.6°C over 30 min. The mean cooling rate was thus 0.9°C/h ± 0.9°C/h, which was statistically significant ($P < .001$). B, Two boxplots of core temperature before and after 30-min warming with Esophageal Cooling Device with a middle plot of individual patients temperature change. Initial core temperature during warming averaged 35.5°C ± 0.5°C (SD), increasing to 35.8°C ± 0.6°C over 30 min. The mean warming rate was thus 0.5°C/h ± 0.6°C/h, which was a significant change (paired *t* test *P* = .001). SD indicates standard deviation.



esophageal heat exchange can supplement catheter-based cooling in cases where more power is necessary or replace it in those where it is not, such as in maintenance of mild hypothermia and possibly fever reduction.

Peripheral tissues serve as a thermal buffer and help protect core temperature by insulating core tissues.[24] Some heat traverses peripheral tissues via conduction but much more via blood-borne convection that occurs at variable rates depending on vasomotor status, especially whether arteriovenous shunts are open or closed.[25] Core temperature thus does not change as fast as might be expected in response to surface warming; for example, core temperature does not begin to increase for a half-hour or longer after forced-air warming is applied to the skin—although peripheral tissue and thus mean body temperature begin to increase immediately.[26] Over a period of hours, core temperature changes are similar whether heat is exchanged across the skin surface or directly from the core. But over short periods, inserting or extracting heat from the core changes core temperature considerably faster. An advantage of esophageal heat exchange is that heat is transferred directly into the core, thus rapidly warming or cooling the core.

Only 20% of autonomic responses such as shivering are controlled by mean skin temperature.[27] In contrast, thermal comfort is 50% determined by skin temperature.[28] Surface cooling thus provokes far more thermal discomfort than direct core cooling, such as provided by esophageal or endovascular heat exchange.

Esophageal heat transfer is determined by a variety of factors, but most importantly by characteristics of esophageal tissue and its perfusion. Human tissues insulate relatively well; thus, most heat is transferred within the body by blood-borne convection. We cannot determine the relative contributions of conduction and convection to observed heat transfer rates, but perfusion almost surely dominates. General anesthesia reduces metabolic rate and cardiac output by about 30%.[29] Whether this reduces esophageal perfusion remains unknown, but it seems likely that esophageal blood flow is comparably reduced. If so, esophageal heat transfer might be somewhat greater in critical care patients. Our patients had a body mass that averaged 29 ± 5 kg/m^2. Increased body mass seems unlikely to substantively influence esophageal heat transfer, but it will proportionately augment the heat transfer required to increase or decrease core and mean body temperatures.

The esophagus is not normally a heat exchange site and presumably is not under thermoregulatory control. Nonetheless, local heating and cooling may well induce vascular responses such as vasodilation that might increase heat transfer during warming or vasoconstriction that might reduce heat transfer during cooling. Consistent with this theory, heat transfer was only a little more than doubled during cooling, although the core-to-fluid gradient was nearly 6 times larger. Both warming and cooling became slightly less efficient over time, perhaps reflecting subtle changes in esophageal blood flow. However, the changes were not of a clinically important magnitude, at least over 30 minutes. It remains possible that heat transfer would be more or less substantial over hours or days.

It is notable that inflow and outflow temperatures of the esophageal perfusion fluid were nearly the same. Three factors may have contributed the following: (1) heat exchange was limited by the relatively poor thermal conductivity of the silicone catheter, (2) catheter surface area was inadequate, and (3) heat exchange was limited by characteristics of the esophagus per se. Among these factors, the first may prove the most important and is amenable to engineering solutions.

The 0.5°C/h increase in core temperature during warming was roughly twice the change in mean body temperature expected from a heat transfer rate of 18 W. Similarly, the 0.9°C/h increase in core temperature was about twice the change in mean body temperature expected from a heat transfer rate of 53 W. The disparity most likely indicates that heat exchange with the core did not have time (over just 30 minutes) to equilibrate with peripheral tissues, a process that can take up to an hour. The time constants for equilibration depend on vasomotor status but have been characterized for flow of heat from the core to peripheral tissues,[29] for direct core cooling with cold fluid,[30] and during cardiopulmonary bypass.[31] Had heat exchange continued longer, the disparity would presumably have been less.

Two patients did not exhibit increases in temperature during the warming cycle. Both were randomized to initial warming and may have still been within the redistribution period. To the extent that other patients may have still been redistributing during the initial heating/cooling period, cooling rates may be overestimated. Extraneous factors such as patient exposure, body habitus, external warming, and room temperature may also have influenced performance.

In summary, esophageal warming transferred 18 W of heat that is considerably less than the 80 W reported with lower or upper body forced-air covers. However, esophageal warming can be used to supplement surface warming or provide warming in cases not amenable to surface warming such as major burns or trauma. As expected, esophageal cooling transferred more than twice as much heat as warming, consequent to the much larger difference between core and water perfusion temperature with cooling (29°C) than warming (6°C). Esophageal cooling extracted less heat than endovascular catheters but can be used to supplement catheter-based cooling in cases where more power is necessary or possibly replace it in those where it is not, such as in maintenance of mild hypothermia and possibly fever reduction. ■

DISCLOSURES

Name: Prathima Kalasbail, MD.
Contribution: This author helped recruit the patients; acquire the data; and cowrite, review, and approve the manuscript.
Conflicts of Interest: None.
Name: Natalya Makarova, MSc.
Contribution: This author helped as the primary statistician, and helped review and approve the manuscript.
Conflicts of Interest: None.
Name: Frank Garrett.
Contribution: This author helped acquire the data, and review and approve the manuscript.
Conflicts of Interest: F. Garrett is the principal of Garrett Technologies, Inc, which is an independent product development firm. Garrett Technologies developed the Esophageal Cooling

Device and continues to provide design services, but neither Frank Garrett nor his company has a financial interest in the tested system.
Name: Daniel I. Sessler, MD.
Contribution: This author helped design the study; supervise all aspects of the study; and cowrite, review, and approve the manuscript.
Conflicts of Interest: None.
This manuscript was handled by: Maxime Cannesson, MD, PhD.

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