

Anesthesiology
80:671-679, 1994
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Comparison of Forced-air Patient Warming Systems for Perioperative Use

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Background: Perianesthetic hypothermia is common and produces several complications, including postoperative shivering, decreased drug metabolism and clearance, and impaired wound healing. Forced-air warming transfers more than 50 W to the body and is an efficient method for either preventing or reversing decreases in core temperature.

Methods: The authors compared the efficacy of four complete forced-air warming systems: (1) Bair Hugger 250/PACU Patient Warming System with 300 Warming Cover (Augustine Medical, Eden Prairie, MN); (2) Thermacare TC1000 Power Unit with TC1050 Comfort Quilt (Gaymar Industries, Orchard Park, NY); (3) WarmAir 130 Hypothermia System with 140 Warming Tube (Cincinnati Sub-Zero Products, Cincinnati, OH); and (4) WarmTouch 5000 Patient Warming System and 503-0810 CareQuilt (with the connecting hose compressed [short] and extended [long]) (Mallinckrodt Medical, St. Louis, MO). Six minimally clothed male volunteers were studied supine in a 24.5°C environment. Cutaneous heat flux and skin temperature was measured at 14 area-weighted sites using thermal flux transducers. After 20-min control periods, volunteers were warmed for 40 min in each condition. A cotton blanket was placed over each cover. Power units were placed at the foot end of the bed, started cold, and set at maximum temperature and flow settings. All units reached maximum efficiency within 20 min.

Results: Total heat transfer with the Bair Hugger system (95 ± 7 W) was greater ($P < 0.05$) than with WarmTouch (short hose 81 ± 6 W and long hose 68 ± 8 W), Thermacare (61 ± 5 W), and WarmAir (38 ± 6 W) systems. Each cover also was

tested on a common power unit (Bair Hugger 200). Total heat transfer was greater ($P < 0.05$) with the Warming Cover (Bair Hugger) (88 ± 8 W), followed by the Comfort Quilt (Thermacare) (56 ± 6 W), CareQuilt (WarmTouch) (50 ± 7 W), and the Warming Tube (WarmAir) (43 ± 6 W).

Conclusions: The advantages of the Bair Hugger system and Warming Cover are evident in areas that are important for heat transfer from the periphery to the body core (chest, axilla, abdomen, and upper legs). (Key words: Equipment: thermal heat flux transducers. Hypothermia: perioperative; postoperative. Temperature: heat transfer. Temperature, regulation: warming devices.)

ANESTHETIZED patients often become hypothermic during surgery¹ as a result of redistribution of heat from the warm core thermal compartment to cooler peripheral tissues after induction,² increased evaporative heat loss from surgical incisions,³ and inhibition of normal thermoregulatory heat production and retention mechanisms.⁴ It is therefore appropriate either to prevent the onset of hypothermia or at least to minimize the chance of resulting complications by rapidly restoring normal core temperature.

Because 90% of metabolic heat is lost from the skin, it may be clinically important to prevent heat loss from, and even transfer heat to, this surface.⁵ Passive insulation with a single layer of various covers has been shown to reduce total body heat loss about 30%, from approximately 100 to 60–75 W.⁶ Warming the covers before application, or using as many as three layers, provides only slight additional benefit.⁷ Infrared lamps or a Thermal Ceiling (Aragona, River Vale, NJ) are no more effective than passive insulation.⁸ In contrast, heated circulating-water blankets (positioned over patients) reduce net heat loss to zero, and forced-air warming transfers a significant amount of heat (about 50 W) into the body.⁸

The purpose of the current study was to determine the heat transfer efficiency of several complete forced-air warming systems (*i.e.*, power unit with its own cover). Because it is possible to interchange the covers of some systems with power units of others, we also tested each of the system covers using one common

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Received from the University of Manitoba, Winnipeg, Canada; Defense and Civil Institute of Environmental Medicine, North York, Canada; and the University of California, San Francisco. Accepted for publication November 22, 1993. This study was supported by Augustine Medical and the Manitoba Health Research Council grant 3123. Presented in part at the International Anesthesia Research Society 67th Congress, San Diego, California, March 22, 1993.

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power unit. Cutaneous heat loss or gain was measured using thermal flux transducers in normothermic, non-anesthetized volunteers.

Materials and Methods

Six male volunteers (age 23–39 yr, height 177–183 cm, and weight 70.5–83.3 kg) were studied after giving informed consent (table 1).

Instrumentation

Aural canal temperature was measured by a flexible cotton covered thermocouple probe (Mon-a-Therm, Mallinckrodt Medical, St. Louis, MO). The aural probe was inserted by the subjects until they felt the thermocouple touch the tympanic membrane. Proper placement was confirmed when subjects easily detected a gentle rubbing of the attached wire. The probe was then taped in place, the aural canal occluded with cotton, and tape was placed over the external ear.

Cutaneous heat flux (watts per squared meter) and temperature (degrees Celsius) were measured from 14 skin-surface sites by thermal flux transducers (Concept Engineering, Old Saybrook, CT). The transducers were calibrated using a Rapid-k instrument (Dynatech, Cambridge, MA) according to the method of Ducharme *et al.*⁹ Flux was defined as positive when heat traversed skin toward the environment. Body surface area was calculated ($\text{area [squared meters]} = \text{weight}^{0.425} [\text{kilograms}] \times \text{height}^{0.725} [\text{centimeters}] \times 0.007184$) and the following regional percentages were assigned: medial chest 4.5%, lateral chest 5%, medial abdomen 5%, lateral abdomen 4.5%, medial upper arm 3.5%, lateral upper arm 3.5%, anterior forearm 5%, hand 5%, back (and posterior legs) 28%, lateral thigh 7.5%, medial thigh 7.5%, medial calf 4.5%, lateral calf 4.5%, and foot 6%. Flux values from each transducer (watts per squared meter) were then converted into $W \cdot \text{region}^{-1}$ ($\text{flux at region [watts]} = \text{transducer flux [watts per squared meter]} \times \text{body surface area [squared meters]} \times \text{regional percentage} \times 0.01$). In pilot studies, head heat flux (8–9 W) did not differ significantly among the systems. To obtain a more detailed analysis of heat transfer beneath the covers, all transducers were placed under the covers. Because the head represents 6% of the body surface area, calculations represent actual heat transferred, by the covers, to 94% of the body. Weighted mean skin temperatures were determined using the same regional percentages.

Table 1. Patient Characteristics

Patient No.	Side	Age (yr)	Height (cm)	Weight (kg)	Body Surface Area (m ²)
1	L	23	176.5	74.1	1.90
2	L	30	182	79.5	2.00
3	L	23	180.3	70.5	1.89
4	R	39	180.3	83.3	2.03
5	R	23	183.0	75.0	1.96
6	R	34	183.0	78.1	2.00
Mean		28.7	180.9	76.7	1.96
SD		6.2	2.2	4.1	0.05

Side = side on which heat flux transducers were applied ipsilaterally for all conditions; L = left; R = right. There are no significant differences between the two subgroups for any variable.

Analog data from the thermocouples and thermal flux transducers were acquired using an electrically isolated Macintosh IIfx computer equipped with a NB-MIO-16L 16-channel analog-to-digital converter (National Instruments, Austin, TX). Data were digitized asynchronously at 2 Hz, averaged over 5 s, and scaled using appropriate corrections and, where applicable, 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 5-min intervals. The process was controlled by a "virtual instrument" written using LabVIEW II graphical signal processing software (National Instruments).

Warming Units

We tested four forced-air systems: (1) Bair Hugger 250/PACU Patient Warming System with 300 Warming Cover (Augustine Medical, Eden Prairie, MN); (2) Thermacare TC1000 Power Unit with TC1050 Comfort Quilt (Gaymar Industries, Orchard Park, NY); (3) WarmAir 130 Hypothermia System with 140 Warming Tube (Cincinnati Sub-Zero Products, Cincinnati, OH); and (4) WarmTouch 5000 Patient Warming System with 503-0810 CareQuilt (Mallinckrodt). The forced-air power units inject warm air through a connecting hose into disposable plastic or paper quiltlike blankets or, in one case (WarmAir), a U-shaped tube. Warm air exits holes or slits on the patient side of the covers and provides convective warming to the skin. The hose inlets are at the ends of the covers either along the midline or, in one case (WarmTouch), in one corner. The length of the connecting hose on the WarmTouch power unit can be varied roughly by a factor of 2. In contrast hose length is constant for the other units. Therefore the

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WarmTouch system was tested in "short-hose" and "long-hose" conditions. The four covers also were tested using a separate common power unit (Bair Hugger 200) that has been commercially available for some time. § Before the study the output temperatures of the power units were checked to confirm that they met manufacturer specifications.

Protocol

Subjects reported to the laboratory on 2 or 3 days, during which several products and combinations were tested (see Data Analysis). They were minimally clothed, reclined on a 80 × 185-cm hospital bed with an 8.5-cm-thick mattress, and were studied in a 24.5 ± 0.8°C environment. The subjects were randomly assigned to one of two subgroups in which thermal flux transducers were placed ipsilaterally on either the right or left side of the body; the same side was used for each subject on each study day. These subgroups were created because the input for the WarmTouch CareQuilt is not central, but located at one corner of the cover. The two subgroups were similar according to the anthropometric variables listed in table 1. Data from the left and right subgroups were averaged for each condition.

After instrumentation, subjects reclined uncovered in the supine position, with a pillow beneath the head, for a 20-min control period. They then were warmed below the neck for 40 min, for each condition, according to manufacturer's instructions. One cotton blanket was placed over each cover. Subject position was controlled throughout each data acquisition period as follows. Arm position was controlled by having the subjects lightly grip two handles that had been mounted perpendicularly from the bed, just beside the body such that the arms were relaxed and outstretched. A small spacer (3 cm wide) was placed between the feet to maintain a constant foot position. Power units were started cold and set at maximum temperature and air flow settings. Between trials, covers were removed; the subjects sat up; and they were cooled with electric fans to return mean skin temperature and total heat flux to control values. These intertrial periods lasted 30–50 min. The order of conditions was randomized and there were no interday differences in environmental condi-

tions or subject control mean skin temperature and heat flux values.

Data Analysis

Data for each warming system are presented from the conditions using the best cover available from each manufacturer (if multiple models were available) with the respective power units set at maximum temperature and air flow settings. Data from the best cover also are presented for the conditions using the common power unit.

Separate analyses were performed for the complete systems conditions and for the individual covers with the common power unit. Results (means ± SD) are averaged for successive 10-min epochs, with the first two epochs representing 20 min of control and the subsequent four epochs representing 40 min of warming. Differences in the measured parameters over time and among conditions were analyzed using repeated-measures analysis of variance for incomplete block design and were considered statistically significant at the $P < 0.05$ level.

Results

Complete Systems Trials

Mean ambient temperature for these trials was 24.7 ± 0.6°C with no consistent or significant differences for any system condition. The Bair Hugger system transferred the most total heat followed, in order of efficacy, by WarmTouch (short and long hose), Thermacare and WarmAir (fig. 1). During the 20-min control period, total heat flux was stable (*i.e.*, no differences between the two 10-min epochs of control) and there were no differences among systems. All systems reached maximum efficacy within 20 min. During the first warming epoch (0–10 min) heat flux values with the Bair Hugger and WarmTouch (short and long hose) were similar to each other, but significantly greater than the other two systems. During the final three warming epochs, heat flux produced by each system was significantly different than the other systems, except between WarmTouch (long hose) and Thermacare. Total heat flux was significantly less than control values during all warming epochs with each system.

The Bair Hugger system transferred more heat to the upper body (trunk and arms) than did the other systems (fig. 2). Thermacare and WarmTouch (short and long hose) were more efficient than WarmAir but not sig-

§ The manufacturers of this power unit recommend against using other blankets with this product and will not guarantee the unit if this is done.

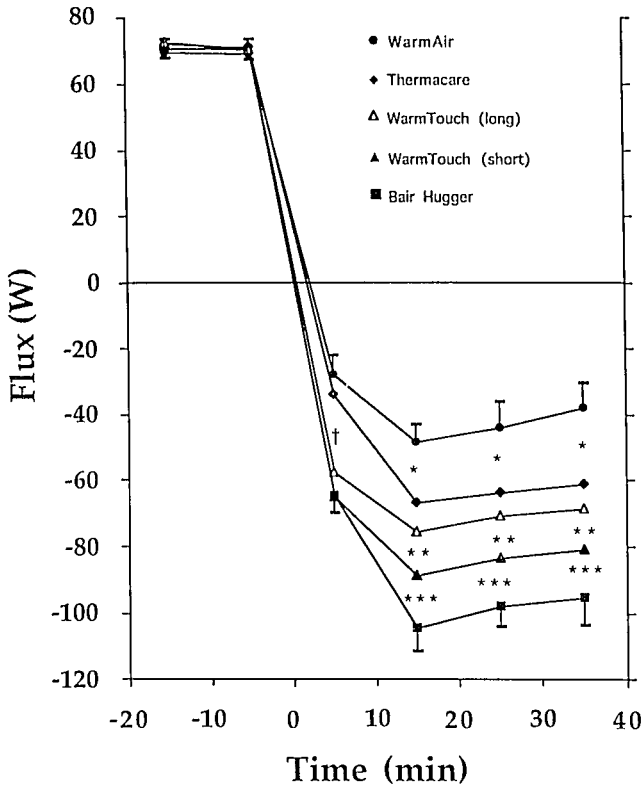


Fig. 1. Total heat flux (excluding the head) during the 20-min control period and 40 min of warming (warming started at 0 min) for each complete warming system. Negative values indicate heat transfer to the skin from the warming systems. The following differences are significant ($P < 0.05$): ***Bair Hugger, greater heat transfer than all other systems; **WarmTouch (short hose), greater heat transfer than other systems except Bair Hugger; *WarmAir, less heat transfer than all other systems; †Bair Hugger and WarmTouch (short and long hose), greater heat transfer than the other two systems.

nificantly different from each other. The Bair Hugger and WarmTouch (short and long hose) warmed the lower body more effectively than the other systems (fig. 3).

Mean skin temperature was stable during the 20-min control period, and there were no differences among the system conditions (fig. 4). With each system, mean skin temperature was significantly different from control during all warming epochs. There were no significant differences among systems until after the first warming epoch. During the final warming epoch, mean skin temperature was greater with Bair Hugger than WarmTouch (long hose) and WarmAir but not Thermacare ($P = 0.054$) or WarmTouch (short hose). Mean

skin temperature was less with WarmAir than the other 4 conditions. Maximum foot temperatures with WarmAir and WarmTouch (short- and long-hose conditions) were 36.7 ± 0.8 , 36.1 ± 1.2 and $36.5 \pm 0.6^\circ\text{C}$, respectively. These values were not different from each other but were significantly greater than foot temperatures for Thermacare (35.5 ± 1.0) and Bair Hugger (34.9 ± 1.5) ($P < 0.05$).

The average increase in aural canal temperature from baseline to the final epoch were as follows for each system: Bair Hugger, $0.24 \pm 0.10^\circ\text{C}$; WarmAir, $0.19 \pm 0.21^\circ\text{C}$; Thermacare, $0.13 \pm 0.10^\circ\text{C}$; WarmTouch (long hose), $0.22 \pm 0.09^\circ\text{C}$; and WarmTouch (short hose), $0.08 \pm 0.17^\circ\text{C}$ (fig. 5). One-tailed paired t test indicated that the change from baseline was significant during the Bair Hugger and the WarmTouch (long hose) conditions ($P < 0.05$).

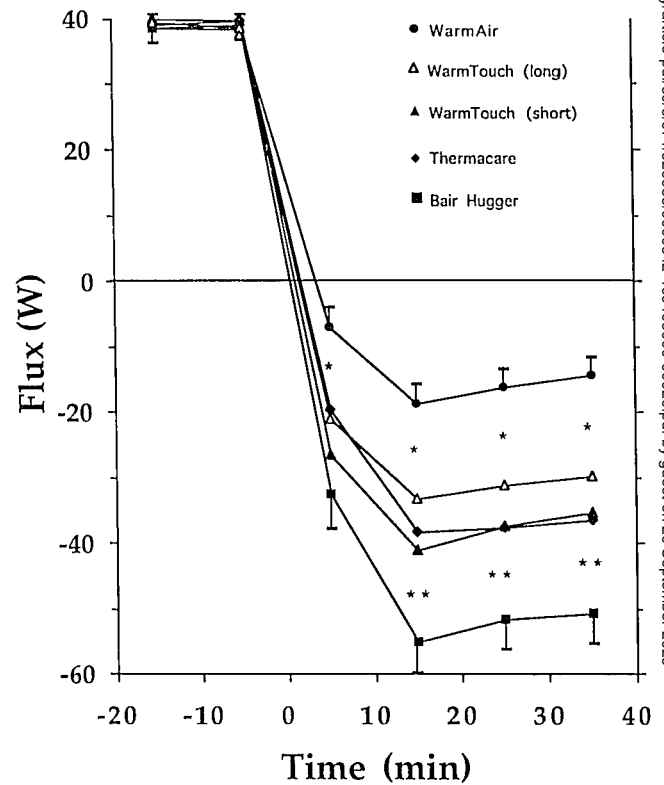


Fig. 2. Upper-body heat flux (torso and arms) during the 20-min control period and 40 min of warming (warming started at 0 min) for each complete warming system. The following differences are significant ($P < 0.05$): **Bair Hugger, different from all other systems; *WarmAir, different from all other systems.

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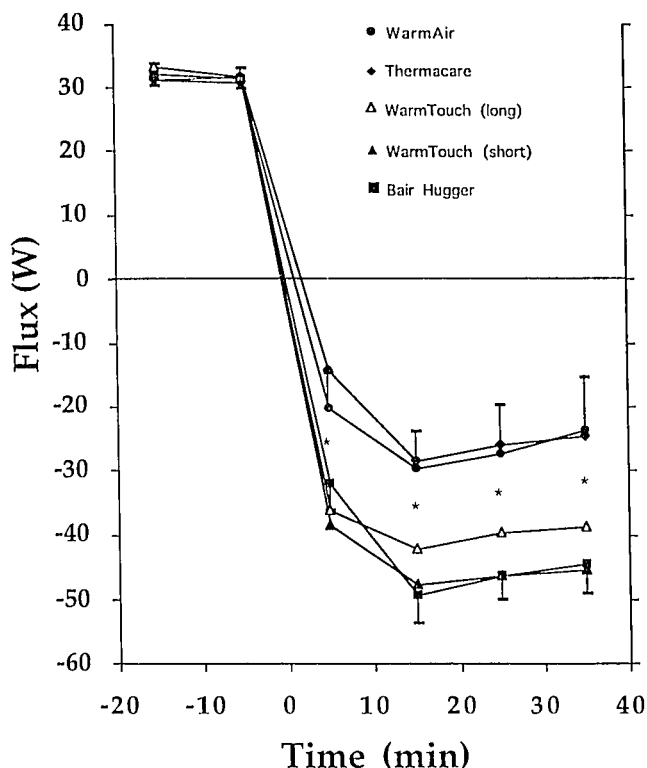


Fig. 3. Lower-body heat flux during the 20-min control period and 40 min of warming (warming started at 0 min) for each complete warming system. *Bair Hugger and WarmTouch (short and long hose), different from Thermacare and WarmAir ($P < 0.05$)

Individual Covers with a Common Power Unit

Mean ambient temperature was $24.3 \pm 0.7^\circ\text{C}$ during these trials. There were no consistent or significant differences among cover conditions or when compared with the system conditions. When the covers from each manufacturer were compared using a common power unit (Bair Hugger 200), total heat transfer and mean skin temperature with the Bair Hugger Warming Cover were greater than the other three covers, which were similar to each other (figs. 6 and 7). The following differences in aural canal temperature between baseline and the final epoch were not significant: Warming Cover (Bair Hugger), $0.13 \pm 0.12^\circ\text{C}$; Warming Tube (WarmAir), $0.11 \pm 0.14^\circ\text{C}$ ($P < 0.05$); Comfort Quilt (Thermacare), $0.08 \pm 0.23^\circ\text{C}$; and CareQuilt (WarmTouch), $-0.01 \pm 0.18^\circ\text{C}$ (fig. 5).

There was a significant correlation between total heat flux and average skin temperature during all trials. These variables were related by the equation: flux

(watts) = $1,209 - 34.4 \cdot \text{temperature (degrees Celsius)}$ ($r^2 = 0.78$).

Discussion

Forced-air warming is the most effective noninvasive clinical method of transferring heat to the body.⁸ In our comparison of four complete forced-air systems, total heat transfer and increase in average skin temperature was greatest with the Bair Hugger system, followed in order of efficacy by WarmTouch (short and long hose), Thermacare, and WarmAir systems. To further compare the heat transfer efficacy of the individual warming covers, independent from possible differences in power unit output, the covers also were tested on a common power unit (Bair Hugger 200). In these trials, total heat transfer to the body was greatest with the

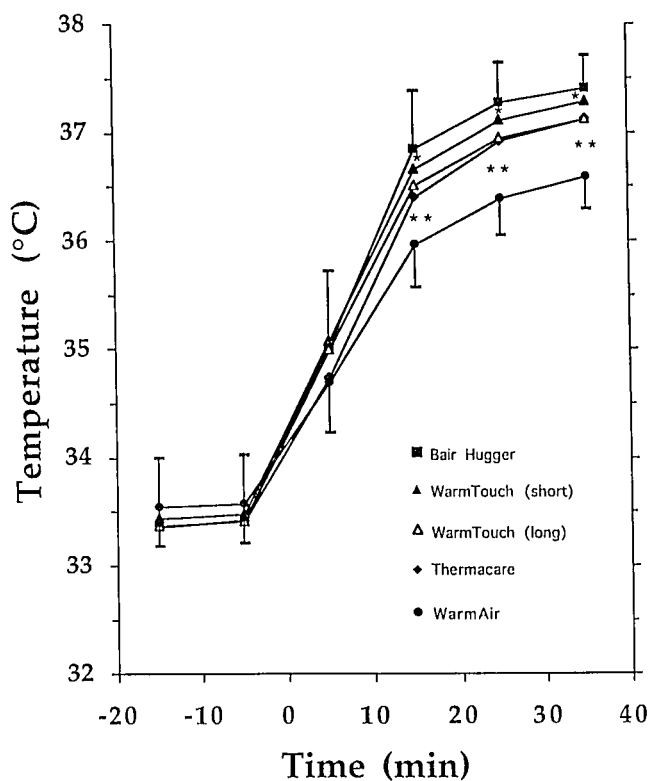


Fig. 4. Mean skin temperature (excluding the head) during the 20-min control period and 40 min of warming (warming started at 0 min) for each complete warming system. The following differences are significant ($P < 0.05$): **WarmAir, different from all other systems; *Bair Hugger, different from WarmTouch (long hose) and WarmAir.

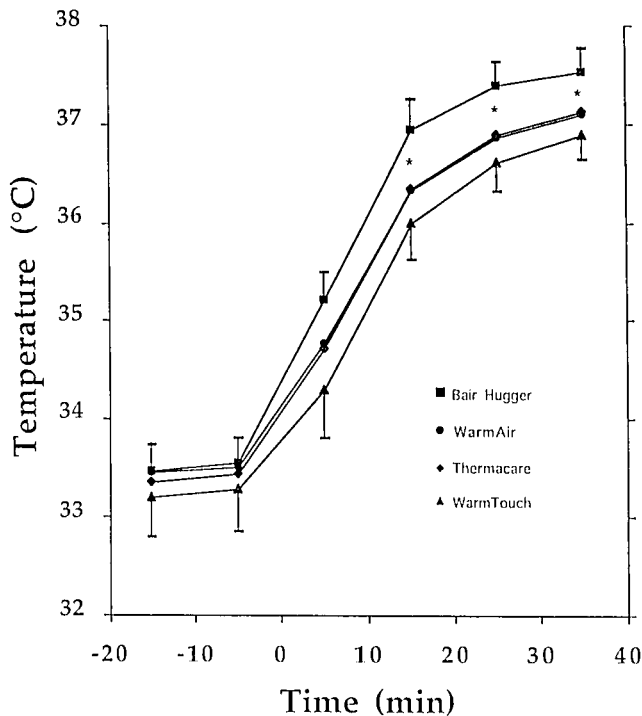


Fig. 5. Mean skin temperature (excluding the head) during the 20-min control period and 40 min of warming (warming started at 0 min) for each cover, using a common power unit (Bair Hugger 200). *Warming Cover (Bair Hugger), significantly different from all other covers ($P < 0.05$).

Warming Cover (Bair Hugger) followed by the Comfort Quilt (Thermacare), CareQuilt (WarmTouch) and the Warming Tube (WarmAir).

The maximal intercondition differences in heat transfer were approximately 57 W in the systems comparison and approximately 45 W in the blankets comparison. These results are clinically significant for the following reasons. The magnitude of differences among some conditions approaches the entire metabolic heat production of an anesthetized patient, and is greater than the decrease in heat loss that results from covering a patient with three cotton blankets.⁷ Although non-anesthetized subjects were studied, the qualitative differences among conditions would be maintained in anesthetized patients. During surgery, in which a large surface area is exposed with less area available for warming, the differences among some of these systems or blankets would be important. Recovering hypothermic patients will vasoconstrict once anesthetic effects dissipate and thermoregulatory control is restored.

Under these conditions, transfer of heat from the periphery to the core will be reduced.¹⁰ However, it is likely that the system that transfers the most heat will still provide a rewarming advantage.

Forced-air warming provides convective warming by passing heated air across the skin. Heat then is transferred from the warmed surface to the body core mainly *via* convection (blood flow); convection is most effective in areas with major blood vessels in close proximity to the skin surface (*i.e.*, chest, axilla, abdomen, and groin).¹¹ The pattern of skin warming and efficacy of heat transfer can be explained, in part, by the cover designs. The Warming Cover (Bair Hugger) and Comfort Quilt (Thermacare) have hose inlets located centrally near the foot end. Both covers direct a main stream of air toward the head *via* a central channel. Air is then directed laterally from the central channel to the sides of the covers. The central channel is important for directing more heat to important heat transfer areas of the body. The CareQuilt (WarmTouch) has the hose inlet on one corner and does not have a central

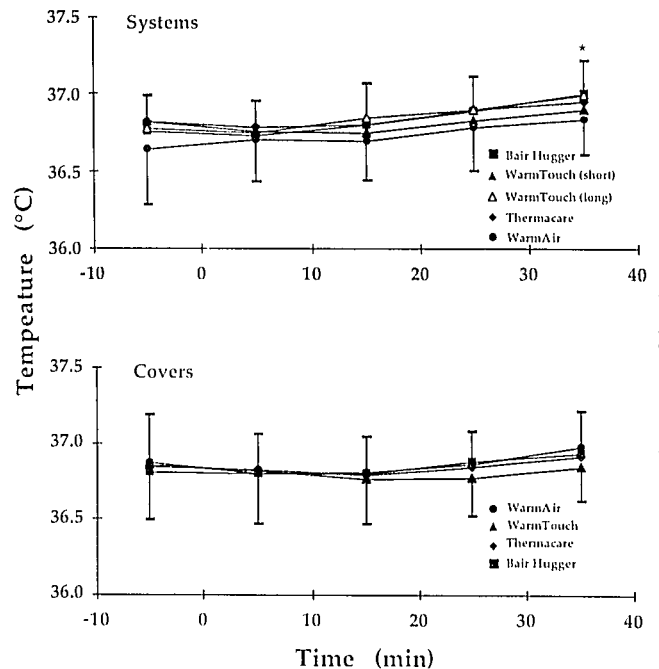


Fig. 6. Aural canal temperatures during the last 10-min period before warming and 40 min of warming (warming started at 0 min) for each complete system (*top*) and for each cover using a common power unit (Bair Hugger 200) (*bottom*). *Significant increase from baseline to final epoch with Bair Hugger and WarmTouch (long hose) ($P < 0.05$).

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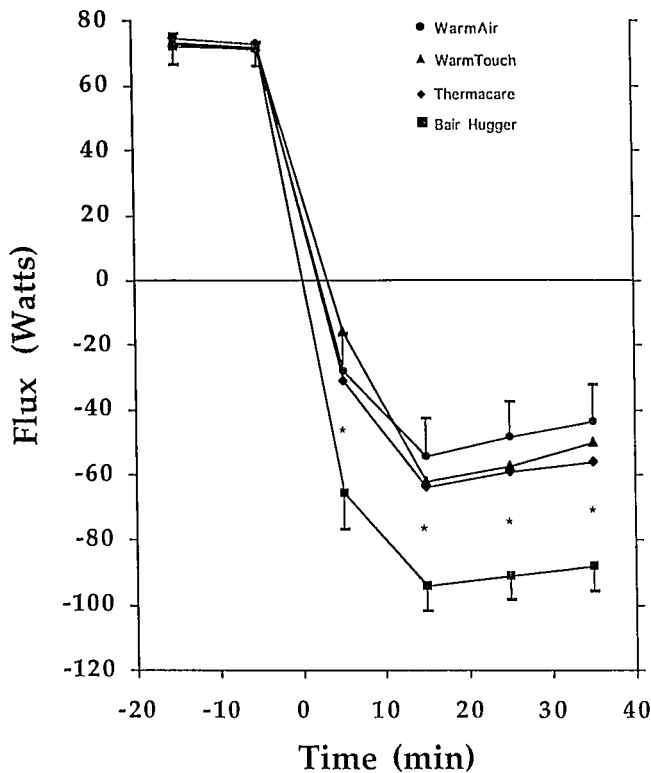


Fig. 7. Total heat flux (excluding the head) during the 20-min control period and 40 min of warming (warming started at 0 min) for each cover, using a common power unit (Bair Hugger 200). *Warming Cover (Bair Hugger) significantly different from all other covers ($P < 0.05$).

channel to direct heat to the other end of the cover. For instance, when compared to values obtained with the Warming Cover (Bair Hugger), leg heat flux with the CareQuilt (WarmTouch) is similar, whereas values of chest and abdomen flux are 13 W less. The U-shaped Warming Tube (WarmAir) does not cover the body completely but rather lies beside the legs and feet and on top of the arms. The central hose inlet is at the foot end and the tube is designed to blow air medially. This configuration maximizes air flow toward the body. However, our data suggest that little heat is transferred

|| The WarmTouch Comfort Quilt can also be oriented with the power unit hose inlet at the head end. We did not test this condition because we wanted to standardize the power unit location. We also surveyed several North American PACU units; the majority indicated that they would not place a power unit at the head end of the bed because of space limitations.

by convection to the anterior trunk, medial legs and arms when the Warming Tube (WarmAir) is covered by a cotton blanket. The cotton blanket probably attenuates medial movement of warmed air wherever it rests on the skin.

In the current study, baseline heat loss was 30–55 W less and the average skin temperature 1.5–2.5°C higher than previously reported by Sessler and Moayeri.⁸ The first of several reasons for these differences is that our ambient temperature was 3.5–4.0°C higher in order to approximate Post Anesthesia Care Unit (PACU) conditions more closely. A comparison of data from two other studies by Sessler and colleagues^{6,12} indicates a 40-W difference in baseline heat flux when ambient temperatures differ by about 10°C. Thus, the effect of higher ambient temperature would account for a 14-W-lower baseline heat loss in our study. Second, the higher baseline flux demonstrated previously⁸ may be partly due to the use of different heat flux transducers. If factory calibrations are used, the transducers used in this original study may overestimate flux by as much as 20%,⁹ compared with the transducers used in subsequent studies by Sessler and colleagues^{6,12} and our current study. This may account for a 20–25-W difference. Third, we did not include heat flux from the head because we chose to report the heat transfer only under the covers. Head heat flux (about 8–9 W) did not differ greatly among systems or throughout each condition (unpublished pilot data), therefore, exclusion of head heat flux would consistently lower baseline heat loss, and increase heat gain values during warming by this amount. None of these considerations alters the validity of comparisons within any of the reported trials.^{6,8,12}

Our results for warming heat gain also are about 40 W (Systems trials) and 33 W (Covers trials) greater than reported previously.⁸ There are two additional factors contributing to this difference. The 300 Warming Cover (Bair Hugger) used in the current study is a recent design. We have compared the original and recent designs and found 5-W greater heat transfer with the new cover (unpublished results). We also have shown that the Bair Hugger 250/PACU power unit transfers about 7 W more, with a given Warming Cover, than the Bair Hugger 200 unit used previously⁸ (unpublished results). Taking all factors into account, and given the inherent errors in heat flux measurement (see below), our data are comparable to previous work in this area.

The main safety concern with any warming method, is burn prevention. The probability of burns depends on temperature and length of warming, and is inversely related to perfusion of the warmed area. Perfusion may be compromised either intrinsically (thermoregulatory or other control mechanisms^{1,3} and vascular insufficiency¹⁴⁻¹⁶) or extrinsically (external pressure exerted by the warming device).¹⁶⁻¹⁸ Perfusion is not likely to be compromised by external pressure with any of the warming covers tested in the current study. These covers weigh little and, if used with only one cotton blanket on top, air flow through the patient side of the blanket keeps much of the covers from direct contact with the skin. Nevertheless, there are a few reports of burns with forced-air warming. In one case, the wrong side of the warming cover was applied to the skin; in another, the patient had severe vascular disease and was inadequately monitored.[#]

The highest foot temperatures were seen with WarmAir (37.7°C). The highest leg skin temperatures were measured on the medial thigh (~38.0–38.5°C) in the Bair Hugger and WarmTouch (short-hose) conditions. The critical temperature for burns, with an exposure time comparable to length of forced-air warming therapy in recovery (1–3 h), is about 43°C.¹⁹ Therefore, all units tested seem to provide a safe level of rewarming for well perfused patients, provided they are properly used.

Measurements of heat flux and average skin temperature are subject to errors resulting from regional differences in temperature and flux, as well as errors in estimating regional skin areas. To minimize these errors, we recorded temperature and heat flux at 14 sites. Heat loss values obtained with this technique, and from a similar number of sites, compare favorably to calorimetric values²⁰ (Snellen, personal communication). To the extent that some quantitative errors may occur, they would be comparable among conditions, thus comparisons of systems and covers are qualitatively valid. Because the CareQuilt (WarmTouch) has the hose inlet on one corner, ipsilaterally placed discs do not provide an accurate representation of whole body effects for this cover. We used an even number of subjects so that average data would include the same number of data points from either side. Because there were

no significant differences in weight, height, or body surface area between the two subgroups (greater body surface area would increase the calculated heat flux values), group data should accurately describe whole body effects.

In conclusion the Bair Hugger Patient Warming System is the most efficient in terms of total heat transfer to the body when compared to three other forced-air warming systems. This advantage is due to superiority in areas important for heat transfer to the body core (chest, axilla, abdomen, and upper legs). The skin temperatures observed with any of these forced-air systems are unlikely to promote burns if the covers are properly applied to appropriate patients.

The authors thank Dr. Carl Schwartz of the University of Manitoba Statistics Department for his assistance in statistical analysis.

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