Conductive Heat Exchange with a Gel-Coated Circulating Water Mattress

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The use of forced-air warming is associated with costs for the disposable blankets. As an alternative method, we studied heat transfer with a reusable gel-coated circulating water mattress placed under the back in eight healthy volunteers. Heat flux was measured with six calibrated heat flux transducers. Additionally, mattress temperature, skin temperature, and core temperature were measured. Water temperature was set to 25°C, 30°C, 35°C, and 41°C. Heat transfer was calculated by multiplying heat flux by contact area. Mattress temperature, skin temperature, and heat flux were used to determine the heat exchange coefficient for conduction. Heat flux and water temperature were related by the following equation: heat flux = 10.3 × water temperature − 374 (r² = 0.98). The heat exchange coefficient for conduction was 121 W · m⁻² · °C⁻¹. The maximal heat transfer with the gel-coated circulating water mattress was 18.4 ± 3.3 W. Because of the small effect on the heat balance of the body, a gel-coated circulating water mattress placed only on the back cannot replace a forced-air warming system.

Forced-air warming is now the method of choice for the prevention of perioperative hypothermia because of its well documented efficacy. However, the use of forced-air warming is associated with costs for the disposable blankets. This leads to a growing interest for alternative active warming methods working without single-use products (1). One possible method is conductive warming by circulating water mattresses. After the introduction of forced-air warmers, various authors suggested that forced-air warmers were more effective than circulating water mattresses (2,3). However, the potential heat exchange area to which a circulating water mattress can be applied (e.g., front and back of the body with multiple covers) is larger than the area covered by a forced-air warming blanket, and when this area advantage was exploited, a circulating water mattress was better able to maintain normothermia than a forced-air warming system (4). Circulating water mattresses exchange heat by conduction, and, therefore, good contact between the water mattress and the skin is essential. A gel coating of these circulating water mattresses could enhance contact between the mattress and the body, thereby increasing efficacy. A device like this has not been studied in humans. Therefore, we studied conductive heat exchange with a gel-coated circulating water mattress in volunteers.

Methods

After ethics committee approval and written, informed consent, we studied 8 minimally clothed healthy volunteers (4 men and 4 women) aged between 24 and 31 yr. For conductive warming via the back, we used a circulating water mattress (Comfort-Pad Plus®, Cincinnati Sub-Zero Products Inc., Cincinnati, OH) that incorporates a gel coating (Granulab International, Armersfoort, The Netherlands). The gel coating covers the water mattress on both sides and is approximately 5 mm thick. The mattress measures 56.5 × 76 cm (0.43 m²). The water of this mattress was heated by a hypo-hyperthermia system (Hico-Variotherm 530; Hirtz & Co. Hospitalwerk, Cologne,
Germany). Room temperature, relative humidity, and air velocity were measured by using a thermoanemometer (Velocicalc Plus TSI® Model 8388-M-D; TSI Incorporated, St. Paul, MN).

To measure the heat flux (heat flow per unit area) between the water mattress and the back of the volunteers, we used six heat flux transducers (Heat Flow Sensor Model FR-025-TH44033-F16; Concept Engineering, Old Saybrook, CT). The heat flux transducers were calibrated with a Dynatech R-Matic heat-flow meter (Dynatech, Cambridge, MA). The calibration conforms to American Society for Testing and Materials C-518, the standard test method for measuring steady-state thermal transmission by means of a heat-flow meter. The overall average accuracy of calibration is expected to be ±3%. The heat flux transducers were attached to the back of the volunteers with thermal conductive paste and a plaster ring (Double-Stick™ Disk, 3M, St. Paul, MN). Heat flux from the back of the volunteer to the water mattress was called “heat loss” and was assigned a negative value. Heat flux from the water mattress to the volunteers was called “heat gain.”

Mattress temperature was measured with six thermocouples (MAT Myocardial sensor, 18 mm; Mallinckrodt Medical, Hennef/Sieg, Germany). Skin temperature at the back of the volunteers was measured with calibrated thermistors incorporated into the heat flux sensors, and core temperature was measured at the tympanic membrane by using an infrared thermometer (Diatek 9000 Instatemp; Medimex, Hamburg, Germany).

On the study day, room temperature, relative humidity, air velocity, and core temperature of the volunteers were measured. Six heat flux transducers were then placed on the back of the volunteers, and six thermocouples were placed on the corresponding surface of the mattress (Fig. 1). The volunteers laid down on the gel-coated circulating water mattress and were covered with two layers of cotton blankets. The water of the hypo-hyperthermia system was initially set to 25°C. After local steady-state conditions (constant heat flow at a constant temperature gradient between the mattress and the skin) were achieved, mattress temperature, skin temperature, and heat flux were sampled and averaged over the next 10 min, and core temperature was measured again. This procedure was repeated for temperature settings of the hypo-hyperthermia system of 30°C, 35°C, and 41°C.

Heat exchange by conduction can be described as follows (5):

$$\dot{Q} = h_K \cdot \Delta T \cdot A,$$

where $\dot{Q}$ indicates heat transfer (W), $h_K$ indicates heat exchange coefficient by conduction (W · m$^{-2}$ · °C$^{-1}$), $\Delta T$ indicates the temperature gradient between the mattress and the skin (°C), and $A$ indicates contact area (m$^2$).

Mattress temperature, skin temperature, and heat flux were used to determine $h_K$. The slope of the least-squares regression of heat flux as a function of the temperature gradient between mattress and skin represents $h_K$.

To determine the contact area between the skin of the volunteers and the gel-coated circulating water mattress, an individual print of each volunteer was produced. The back was coated with body oil, and the volunteer then lay down on a sheet of absorptive paper covering the gel-coated water mattress. The oil marked the contact area pattern on the paper. The contact area was filled with rectangles of appropriate size, and the area was calculated by summing the areas of all rectangles. Heat transfer was calculated by multiplying heat flux by contact area.

All variables are presented as mean ± sd. Linear regressions are presented with the corresponding confidence intervals (CI). Core temperatures before and after the experiment were compared by using Student’s paired $t$-test.
Results

Room temperature was 22.2°C ± 0.2°C, relative humidity was 43% ± 3%, and air velocity was less than 0.12 m/s. The age of the volunteers was 26 ± 2 yr, height was 177 ± 3 cm, and body weight was 72 ± 6 kg.

At a water temperature of 25°C, heat loss per area from the back to the mattress was 120.3 ± 10.2 W/m²; at 30°C it was 60.5 ± 6.3 W/m²; and at 35°C it was 15.6 ± 4.1 W/m². At 41°C a heat gain per area of 46.5 ± 6.6 W/m² appeared. The relationship between the heat flux and the water temperature was linear. The variables were related by the following equation: heat flux = 10.3 (95% CI, 10.1–10.5) W·°C⁻¹ (95% CI, 368–380) (r² = 0.98; n = 192).

The relationship between the mattress temperature and the water temperature was linear. Mattress temperature = 0.50 (95% CI, 0.49–0.50) × water temperature + 17.8 (95% CI, 17.5–18.0) (r² = 0.99; n = 192). Skin temperature increased stepwise from 31.3°C ± 0.4°C to 37.8°C ± 0.2°C. The relationship between the skin temperature and the water temperature was also linear: skin temperature = 0.42 (95% CI, 0.41–0.42) × water temperature + 20.7 (95% CI, 20.4–21.0) (r² = 0.98; n = 192). The core temperature of the volunteers was 36.6°C ± 0.3°C before the investigation and remained constant during the investigation (P > 0.1; Fig. 2).

There was a linear relationship between the heat flux and the temperature gradient between the water mattress and skin that defined the h_K: 121 W·m⁻²·°C⁻¹ (95% CI, 117–125) (r² = 0.95; n = 192; Fig. 3).

The contact area between the gel-coated circulating water mattress and the back of the volunteers was 0.39 ± 0.03 m². Multiplication of the heat flux per area times the contact area gave a heat transfer of 47.5 ± 5.8 W to +18.4 ± 3.3 W, depending on the water temperature. The relationship between heat transfer and the water temperature was also linear: heat transfer = 4.1 (95% CI, 4.0–4.2) × water temperature + 135 (95% CI, 144–151) (r² = 0.97; n = 192).

Discussion

The efficacy of different measures for the prevention of perioperative hypothermia has been examined mostly in clinical studies (1,3,6–9). In these studies, core temperature changes are taken as the measure of efficacy. The measurement of core temperature allows only a limited evaluation of the efficacy of the studied methods. During the first hour after the induction of anesthesia, there is a decrease in core temperature that is mainly caused by redistribution of heat from the core to the periphery of the body and is not related to heat losses (10). However, after several hours, there is a plateau of core temperature caused by reemerging thermoregulatory vasoconstriction, although there is still relevant heat loss to the environment (11).

Another way of studying warming devices is the direct measurement of heat transfer by using manikins (12,13) or volunteers (5,14–16). This method has the advantage that the physical heat exchange characteristics of an active warming system can be evaluated independently of thermoregulatory mechanisms.

The study has three methodological limitations. 1) Core temperature was measured at the tympanic membrane by using an infrared thermometer. Temperature measurement with a tympanic membrane thermocouple is recommended as a “gold standard”...
of core temperature recording. However, use of temperature probes in the auditory canal may lead to damage of the tympanic membrane. Temperature measurement with infrared thermometry does not pose this risk. Although easy to use, infrared thermometry requires extremely careful handling to obtain fairly reliable results. 2) The mattress temperature was sequentially increased and not randomly assigned. However, lack of randomization is unlikely to have influenced the results. 3) It might have been interesting to compare the results of the gel-coated circulating water mattress directly with those of a normal circulating water mattress.

An increase in water temperature from 25°C to 41°C linearly increased the mattress temperature and the skin temperature. Water temperatures of 25°C to 35°C caused heat loss from the back. Only with a water temperature of 41°C did we measure heat transfer from the mattress to the body. In these normothermic volunteers, temperature analysis (Fig. 2) showed that when the water temperature was >36.6°C, the mattress temperature exceeded the skin temperature, so that heat flux from the mattress to the back was possible. Water temperatures between 36.6°C and 37.7°C caused heat transfer to the back of the body, because the temperature of the gel-coated water mattress was higher than the skin temperature. However, because the core temperature was higher than the skin temperature, heat transfer to the core of the body was impossible. Water temperatures of >37.7°C produced a skin temperature that was higher than core temperature and, therefore, allowed heat transfer from the skin to the core. In hypothermia, both core and skin temperatures would have been lower than those seen here, and, therefore, skin temperature would have exceeded core temperature at a correspondingly lower water temperature.

The relationship between the measured temperature gradient from water mattress to skin and the observed heat flux was linear (Fig. 3). The slope of this relationship defines the $h_K$ between the gel-coated water mattress and the skin. The $h_K$ is not influenced by the heat balance of the body, core temperature, local circulation, or skin temperature. A change in skin temperature will alter the temperature gradient but will not alter $h_K$ (17). Our $h_K$ for conduction of 121 W·m$^{-2}$·°C$^{-1}$ was higher than the value of 41 W·m$^{-2}$·°C$^{-1}$ reported by English et al. (5) for a conventional water mattress. This can be explained by the gel coating of this water mattress, which enhances contact between the mattress and the back, thereby reducing thermal contact resistance and increasing the efficacy of heat exchange. However, the threefold higher $h_K$ does not necessarily mean that the resulting heat transfer will be threefold higher. With the same estimated contact area, the maximal heat transfer calculated from the data of English et al. was 11.2 W. This heat transfer is more than one-third of the heat transfer with the gel-coated water mattress, 18.4 W, although the water temperature in the study of English et al. was set to only 40°C, whereas we used a temperature setting of 41°C. Therefore, the higher $h_K$ of the gel mattress did not translate into an equivalent higher heat transfer. This was because the superior heat-exchanging properties between the gel-coated water mattress and the skin were constrained by the insulating properties of the gel between the water and the surface of the mattress. The insulation of the gel led to a smaller increase in mattress temperature with increasing water temperature. In our study, mattress and water temperatures were related by the following equation:

$$\text{Mattress temperature} = 0.5 \times \text{water temperature} + 17.8,$$

so a 1°C change in water temperature changed the mattress temperature by 0.5°C. With the conventional water mattress (5), the equation was

$$\text{Mattress temperature} = 0.7 \times \text{water temperature} + 11.2,$$

and a 1°C change in water temperature changed the mattress temperature by 0.7°C. Because of the insulation of the gel, the mattress temperature was less than that of a conventional water mattress for the same water temperature.

The limitations of this gel mattress are due to the insulation of the gel. Because of its insulation, the temperature decrease within the gel system was more than without the gel, so the temperature of the mattress was lower. Heat transfer could be increased by a gel with less insulating properties or a thinner gel layer. The maximal temperature of the gel-coated water mattress was only 38.2°C ± 0.2°C. This is much lower than the limit of 41°C that is given by the international standard CEI/IEC 601-2-35 (18). A higher mattress temperature would increase the temperature gradient and lead to a higher heat transfer. Assuming that the linear relationship between water temperature and skin temperature continues for higher temperatures, a mattress temperature of 40°C at the gel-coated water mattress would produce a maximal heat transfer of 33.4 W, instead of the 18.4 W that we measured under these conditions. Despite these limitations, the maximal heat transfer of 18.4 ± 3.3 W measured in this study was the same as the heat transfer measured with forced-air warming systems with upper body blankets in volunteers (16) and in a manikin (12). The decreased efficacy reported in clinical studies of water mattresses applied only to the back, when compared with forced-air warming (1-3).
applied to the front, can be explained by the smaller effect of the water mattress on the heat balance of the body. During surgery, little heat is lost from the back—approximately 3 to 5 W (2,19). In this study, this would mean that a −5-W heat loss from the back would become a +18.4-W heat gain, for a change in heat balance of 23.4 W. In contrast, forced-air warming systems with upper body blankets change the heat balance about 46.1 to 55 W (16), which means that forced-air warming systems with upper body blankets change the heat balance of the body more than a gel-coated circulating water mattress under the back. Because of the small effect on the body’s heat balance when the gel-coated mattress is placed only on the back, it cannot replace a forced-air warming system. Any heat gain at a site where, without the heating system, there would have been little heat loss (e.g., from the back) will have only a small effect on whole-body heat balance. However, where, in the absence of a heating system, there would have been significant heat loss (e.g., from the front of the body through minimal insulation to the environment), then any heat gain will have a dramatic effect on whole-body heat balance. Therefore, it is sensible to use a circulating water mattress on the back, where it can supply heat that a forced-air warming system cannot, but it should also be used on the front of the body (1,14). The design of all water mattress systems allows one machine to supply multiple mattresses, and this feature, combined with the different sizes of mattresses that are available, means that a water mattress system can be simultaneously used on the posterior and anterior surfaces.

References