Efficacy of forced-air warming systems with full body blankets

[Efficacité des systèmes de chauffage à air pulsé avec des couvertures à champ complet]

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Purpose: Postoperative hypothermia after cardiac surgery is still a common problem often treated with forced-air warming. This study was conducted to determine the heat transfer efficacy of 11 forced-air warming systems with full body blankets on a validated copper manikin.

Methods: The following systems were tested: 1) Bair Hugger® 505; 2) Bair Hugger® 750; 3) Life-Air 1000 S; 4) Snuggle Warm®; 5) Thermacare®; 6) Thermacare® with reusable Optisan® blanket; 7) WarmAir®; 8) Warm-Gard®; 9) Warm-Gard® and reusable blanket; 10) WarmTouch®; and 11) WarmTouch® and reusable blanket. Heat transfer of forced-air warmers can be described as follows: $\dot{Q} = h \cdot \Delta T \cdot A$.

Where $\dot{Q}$ = heat flux (W), h = heat exchange coefficient ($W \cdot m^{-2} \cdot {}^\circ C^{-1}$), ΔT = temperature gradient between blanket and manikin surface (°C), A = covered area (m^2). Heat flux per unit area and surface temperature were measured with 16 heat flux transducers. Blanket temperature was measured using 16 thermocouples. The temperature gradient between blanket and surface (ΔT) was varied and h was determined by linear regression analysis. Mean ΔT was determined for surface temperatures between 32°C and 38°C. The covered area was estimated to be 1.21 m^2.

Results: For the 11 devices, heat transfers of 30.7 W to 77.3 W were observed for surface temperatures of 32°C, and between -8.8 W to 29.6 W for surface temperatures of 38°C.

Conclusion: There are clinically relevant differences between the tested forced-air warming systems with full body blankets. Several systems were unable to transfer heat to the manikin at a surface temperature of 38°C.

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***Objectif** : L'hypothermie postopératoire suivant une chirurgie cardiaque est encore un problème courant, souvent traité à l'aide de couverture chauffante à air pulsé. Cette étude a été menée afin de déterminer l'efficacité du transfert de chaleur de 11 systèmes de chauffage à air pulsé avec des couvertures sur un mannequin de cuivre validé.*

***Méthodes** : Les systèmes suivants ont été testés : 1) Bair Hugger® 505; 2) Bair Hugger® 750; 3) Life-Air 1000 S; 4) Snuggle Warm®; 5) Thermacare®; 6) Thermacare® avec couverture réutilisable Optisan®; 7) WarmAir®; 8) Warm-Gard®; 9) Warm-Gard® et couverture réutilisable ; 10) WarmTouch®; et 11) WarmTouch® et couverture réutilisable. Le transfert de chaleur de systèmes de chauffage à air pulsé peut être décrit de cette façon :* $\dot{Q} = h \cdot \Delta T \cdot A$*, où* $\dot{Q}$ *= flux de chaleur (W), h = coefficient d'échange de chaleur (*$W \cdot m^{-2} \cdot {}^\circ C^{-1}$*),* ΔT *= gradient de température entre la couverture et la surface du mannequin (°C), A = aire couverte (*m^2*). Le flux de chaleur par unité d'aire et la température de surface ont été mesurés à l'aide de 16 capteurs de flux de chaleur. La température de la couverture a été mesurée à l'aide de 16 thermocouples. Le gradient de température entre la couverture et la surface (*ΔT*) était modifié et h a été déterminé par une analyse de régression linéaire. Le* ΔT *moyen a été déterminé entre 32°C et 38°C pour les températures de surface. L'aire couverte a été estimée à 1,21*m^2*.*

***Résultats** : Pour les 11 appareils, des transferts de chaleur de 30,7 W à 77,3 W ont été observés pour une température de surface*

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de 32°C, et entre –8,8 W et 29,6 W pour une température de surface de 38°C.

***Conclusion** : Il existe des différences cliniquement significatives entre les systèmes de chauffage à air pulsé testés avec des couvertures à champ complet. De nombreux systèmes ont été incapables de transférer la chaleur au mannequin à une température de surface de 38°C.*

POSTOPERATIVE hypothermia can occur after cardiac surgery as a consequence of inadequate intraoperative warming strategies and the physiological trespasses of cardiopulmonary bypass. During cardiac surgery, forced-air warming is only possible after completion of saphenous vein harvesting with special sterile blankets. This method reduces heat losses after cessation of cardiopulmonary bypass, but cannot prevent temperature afterdrop completely.[1] Other methods, including sodium nitroprusside induced vasodilatation, and increased pump flow during rewarming on cardiopulmonary bypass,[1] or extended rewarming on cardiopulmonary bypass[2] are also not entirely effective in preventing postoperative hypothermia. Therefore, hypothermia after cardiac surgery remains a significant problem,[3–8] for which external warming devices are usually applied in the early postoperative setting.

The following study compared the efficacy of 11 forced-air warming systems with full body blankets using a validated copper manikin of the human body. The primary outcome variable was the heat transfer at surface temperatures of 32°C to 38°C.

Methods

The following forced-air warming systems were tested:

- Bair Hugger® Model 505 Warming Unit and full body blanket model 300 (Arizant Healthcare Inc., Eden Prairie, MN, USA)
- Bair Hugger® Model 750 Warming Unit and full body blanket model 300 (Arizant Healthcare Inc., Eden Prairie, MN, USA)
- Life-Air 1000 S Warming Unit and Soft-Flex full body blanket (Rüsch GmbH, Kernen, Germany)
- Snuggle Warm® SW-3000 Power Unit and full body blanket SW-2001 (Smiths Industries Medical Systems, Irvine, CA, USA)
- Thermacare® TC3003 Power Unit and full body blanket (Gaymar Industries, Orchard Park, NY, USA)
- Thermacare® TC3003 Power Unit (Gaymar Industries, Orchard Park, NY, USA) and reusable Optisan® full body blanket (Rüsch GmbH, Kernen, Germany)
- WarmAir® Model 134 and full body FiltredFlo™ blanket (Cincinnati Sub-Zero Products, Cincinnati, OH, USA)
- Warm-Gard® Portable Warmer and full body blanket (Luis Gibeck AB, Upplands Väsby, Sweden)
- Warm-Gard® Portable Warmer and reusable full body blanket (Luis Gibeck AB, Upplands Väsby, Sweden)
- WarmTouch™ Patient Warming System 5800 and CareQuilt™ full body blanket (Mallinckrodt Medical Inc., St. Louis, MO, USA)
- WarmTouch™ patient warming system 5800 and reusable MultiCover™ full body blanket (Mallinckrodt Medical Inc., St. Louis, MO, USA).

Measurement of environmental conditions

Room temperature, relative humidity and air velocity were measured in the middle of the room and near the wall using a thermoanemometer (VELOCICALC PLUS TSI® Model 8388-M-D, TSI Inc., St. Paul, MN, USA).

The manikin

The manikin consisted of six copper tubes painted matt-black. Two tubes served as arms (circumference 330 mm, length 705 mm), two as legs (circumference 485 mm, length 750 mm), one as the head (circumference 500 mm, length 330 mm) and one as the trunk (circumference 840 mm, length 740 mm). The total surface area of all tubes was 1.98 m^2. In order to set surface temperature and achieve steady-state conditions, water mattresses (Maxi-Therm®, Cincinnati Sub-Zero Products Inc., Cincinnati, OH, USA) were bonded to the inner surface of the copper tubes. The circulating water was warmed and cooled by a hypo-hyperthermia system (Hico-Variotherm 530, Hirtz & Co. Hospitalwerk, Cologne, Germany).

Heat flow delivered to the blanket

Forced-air warming systems consist of a power unit incorporating an electrical heater and a fan to generate an air flow that is delivered downstream to a blanket. Each manufacturer's heater was connected to the corresponding full body blanket. Temperature control was set to the highest temperature, with exception of the Thermacare® power unit, where the highest temperature recommended for anesthetized patients was used. This temperature setting was used throughout the study and was called the "maximum temperature". The air flow control of the Warm-Gard® power unit was set to "high". All other power units have only one flow rate. The air delivery hose from the power unit to the blanket was fully extended. The blankets were then positioned on the manikin and covered with two layers of cotton sheets.

Measurement of nozzle temperature and air velocity at the nozzle

Nozzle temperature and air velocity at the nozzle were measured using a thermoanemometer (VELOCICALC PLUS TSI® Model 8388-M-D, TSI Inc., St. Paul, MN, USA). Both parameters were measured directly at an adapter which connected the nozzle to the blanket and which contained a mesh (mesh size 1 mm × 1 mm) to create laminar air flow. Air temperature and air velocity were measured at three defined positions evenly distributed on the diameter. The average of these three measurements was taken as the average air temperature and air velocity. Air velocity was multiplied by the area of the adapter to calculate air flow.

Heat flow produced by the power units was calculated as follows:

$$\dot{Q} = F \bullet \Delta T \bullet c \bullet \rho$$

where:

$\dot{Q}$ = heat flow (W)
F = air flow ($L \cdot sec^{-1}$)
ΔT = temperature gradient between the nozzle and the room (°C)
c = specific heat capacity of air ($J \cdot g^{-1}$ $°C^{-1}$)
ρ = density of air at the nozzle temperature ($g \cdot L^{-1}$)

The values of the specific heat capacity of air and the density of air at the nozzle temperature were taken from standard tables.[9]

Heat exchange at the manikin

The basic equation for temperature-dependent heat transfer is:

$$\dot{Q} = h \bullet \Delta T \bullet A \text{ (Eqn. 1)}$$

where:
$\dot{Q}$ = heat flow (W)
h = heat exchange coefficient ($W \cdot m^{-2} \cdot °C^{-1}$)
ΔT = temperature gradient (°C)
A = area (m^2)

This equation can be applied to describe the heat exchange process between a forced-air warming blanket and the manikin. The heat exchange coefficient h defines the efficacy of all the heat exchange mechanisms (radiation, convection, and conduction) between the blanket and the manikin, whereas the temperature gradient ΔT is the driving force of this heat exchange.

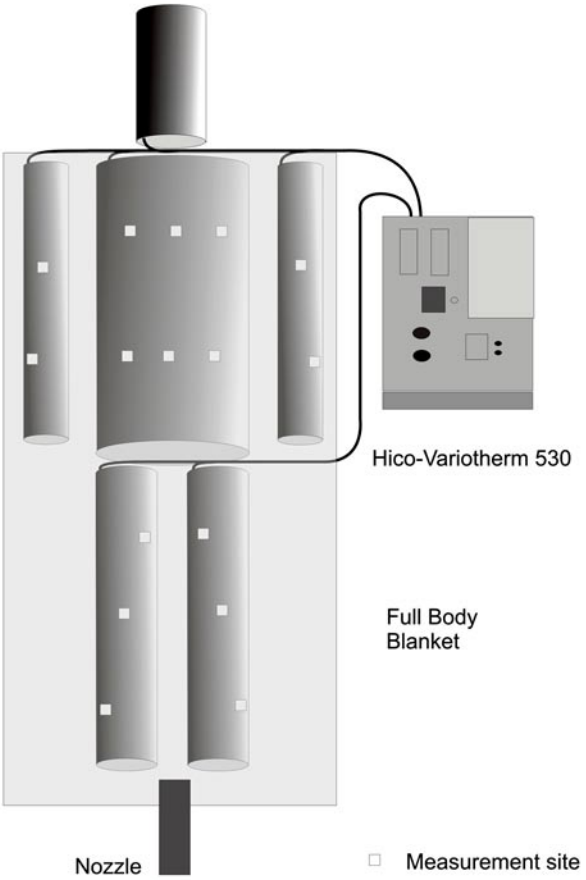

FIGURE 1 Schematic diagram of the manikin and distribution of the 16 measurement sites.

Measurement of heat exchange at the manikin

We measured heat flow per unit area between blanket surface and the manikin with 16 calibrated heat flux transducers (Heat Flow Sensor Model FR-025-TH44033-F16, Concept Engineering, Old Saybrook, CT, USA).

Measurement of temperature gradient

The temperature gradient was defined as the difference between the surface temperature of the manikin underneath the heat flux transducer and the temperature 1 cm above (blanket temperature). Surface temperature of the manikin was measured with thermistors incorporated into the heat flux sensors. To determine the blanket temperature thermocouple needles (MAT Myocardial sensor 18 mm, Mallinckrodt Medical Inc., St. Louis, MO, USA) were used, so that they made direct contact with the surface of the blanket. Both the thermistors and the thermocouples were calibrated before the procedure.

Distribution of measurement sites

Sixteen measurement sites were distributed on the manikin as follows: two sites were placed on each arm, three sites were placed on each leg and six sites were placed on the trunk (Figure 1). On each measurement site heat exchange at the manikin, manikin surface temperature and blanket temperature were measured.

Data sampling

Heat flux signals were measured and digitized using a DASH TC AD-converter (Keithley Instruments Inc., Taunton, MA, USA). The thermistors incorporated in the heat flux transducers for measurement of the manikin surface temperature were connected to Hellige Servomed 236039 monitors (Hellige, Freiburg, Germany). Thermocouples for detection of blanket temperature were connected to a second DASH TC A/D-unit. The signal of these monitors was digitized on a DASH 1402 A/D board (Keithley Instruments Inc., Taunton, MA, USA).

Determination of h

To determine the heat exchange coefficient, heat flux per unit area and temperature differences were measured simultaneously over a range of temperature differences. Eight tests were created by using four different surface temperatures of the manikin (27°C, 32°C, 37°C and 42°C), combined with two different blower temperatures (maximum and room temperature). In this way temperature differences of approximately -10 to +10°C were produced. Each test consisted of a 30-min preparation period to achieve steady state conditions followed by a five-minute measurement period. The collected data were averaged for the single measurement period. In order to randomize the position of blanket perforations in relation to the heat flux transducers each test was repeated three times, each time using a new blanket. The heat exchange coefficient was calculated by linear regression analysis as the slope of heat exchange per unit area as a function of the blanket-surface temperature gradient. The regression line was forced through zero. Heat flux from the blanket to the manikin was called heat gain and was assigned a positive value.

Calculation of mean ΔT for defined surface temperatures

The mean ΔT is dependent on the surface temperature of the manikin and the efficacy of each single system. To compare the different systems it was necessary to derive a mean ΔT for a defined range of manikin surface temperatures. In post-cardiac surgical patients, the mean skin temperature under a forced-air warming blanket ranges between 32°C and almost 38°C.[5,10] Therefore, these surface temperatures were chosen to determine the corresponding mean ΔT. To calculate mean ΔT, the temperature difference between the blanket and the manikin surface was plotted as a function of the temperature of the manikin surface and a regression line was calculated to define their relationship. The equation of this regression line was used to derive mean ΔT for surface temperatures of 32°C and 38°C.

Determination of the covered area

The area covered by the full body blanket was considered to be the same for all systems. Approximately one third of the trunk and the extremities does not take part in heat exchange by forced-air warming, because this surface is in direct contact with the bed. Therefore the covered area was calculated as two thirds of the circumference times the length of the trunk, arms and legs. This resulted in the following covered areas:

Trunk: $2/3 \cdot 0.84\ \text{m} \cdot 0.74\ \text{m} = 0.41\ \text{m}^2$
Arm: $2/3 \cdot 0.33\ \text{m} \cdot 0.705\ \text{m} = 0.16\ \text{m}^2$
Leg: $2/3 \cdot 0.485\ \text{m} \cdot 0.75\ \text{m} = 0.24\ \text{m}^2$
Trunk and extremities: $1.21\ \text{m}^2$

Calculation of heat exchange at the manikin

Heat exchange at the manikin was calculated for surface temperatures of 32°C and 38°C according to equation 1 for each system.

Results

Mean ambient temperature for all trials was 22.1 ± 0.5°C, mean relative humidity was 38 ± 9% and mean air velocity was < 0.1 $\text{m} \cdot \text{sec}^{-1}$ with no relevant difference between the single measurement series.

Heat flow delivered to the blanket

The nozzle temperatures ranged between 41.5°C and 47.6°C and air flow ranged between 9.4 $\text{L} \cdot \text{sec}^{-1}$ and 26.2 $\text{L} \cdot \text{sec}^{-1}$, resulting in heat flows ranging from 249 W to 623 W (Table I).

Heat exchange at the manikin

Total heat flow to the manikin was different for surface temperatures between 32°C and 38°C. At a surface temperature of 32°C the heat flows were higher (between 30.7 and 77.3 W) than at surface temperatures of 34°C (19.9 to 58.5 W) or at a surface temperature of 36°C (8.2 to 44.4 W), or at a surface temperature of 38°C (-8.8 to 29.6 W). The differ-

TABLE I Nozzle temperatures, air flows and the resulting heat flow of the power units

System	*Nozzle temperature (°C)*	*Air flow* ($L\cdot sec^{-1}$)	*Heat flow (W)*
Bair Hugger® 505 and full body blanket	42.8	10.7	249
Bair Hugger® 750 and full body blanket	41.5	26.2	623
Life-Air 1000 S and full body blanket	43.3	15.6	380
Snuggle Warm® SW-3000 and full body blanket	44.5	11.9	297
Thermacare® and full body blanket	42.7	12.8	296
Thermacare® and Optisan® full body blanket	42.8	19.2	447
WarmAir® and full body FiltredFlo™ blanket	42.9	16.4	383
Warm-Gard® and full body blanket	47.6	12.2	346
Warm-Gard® and reusable full body blanket	46.4	9.4	255
WarmTouch™ and CareDrape™ full body blanket	43.1	14.5	342
WarmTouch™ and MultiCover™ full body blanket	44.2	19.8	491

TABLE II Heat exchange coefficients (h), mean temperature gradients at a calculated surface temperature of 32°C (ΔT at 32°C), 34°C (ΔT at 34°C), 36°C (ΔT at 36°C) and 38°C (ΔT at 38°C) and the resulting heat exchange between the full body blanket and the manikin

System	*h*	*ΔT (°C) at*				*Heat exchange (W) at*			
	($Wm^{-2}°C^{-1}$)	*32°C*	*34°C*	*36°C*	*38°C*	*32 °C*	*34 °C*	*36 °C*	*38 °C*
Bair Hugger® 505 and full body blanket	21.9	1.40	0.91	0.43	-0.06	30.7	19.9	11.4	-1.6
Bair Hugger® 750 and full body blanket	28.0	2.76	2.09	1.31	0.53	77.3	58.5	44.4	18.0
Life-Air 1000 S and full body blanket	26.4	1.76	1.17	0.58	-0.02	46.5	30.9	18.5	-0.6
Snuggle Warm® SW-3000 and full body blanket	32.2	1.93	1.42	0.91	0.40	62.1	45.7	35.5	15.6
Thermacare® and full body blanket	23.6	1.97	1.40	0.83	0.26	46.5	33.0	23.7	7.4
Thermacare® and Optisan® full body blanket	17.1	2.79	2.00	1.22	0.43	47.7	34.2	25.2	8.9
WarmAir® and full body FiltredFlo™ blanket	13.4	2.61	1.83	1.05	0.27	35.0	24.5	17.0	4.4
Warm-Gard® and full body blanket	15.4	3.18	2.65	2.12	1.59	49.0	40.8	39.5	29.6
Warm-Gard® and reusable full body blanket	15.3	2.50	1.83	1.16	0.49	38.3	28.0	21.5	9.1
WarmTouch™ and full body blanket	28.1	1.24	0.74	0.24	-0.26	34.8	20.8	8.2	-8.8
WarmTouch™ and MultiCover™ full body blanket	14.5	3.18	2.46	1.74	1.02	46.1	35.7	30.5	17.9

ences between systems were reflected in the higher mean ΔTs at the lower surface temperatures (Table II). The heat exchange coefficients varied by a factor of 2 among the systems and ranged between 13.4 and 32.2 $W\cdot m^{-2}\cdot°C^{-1}$. Figure 2 shows a typical example for the determination of h for a single system.

The mean ΔT varied between 1.24 and 3.18°C for surface temperatures of 32°C and between 0.26 and 1.59°C for surface temperatures of 38°C (Table II). Figure 3 shows a typical example of how mean ΔT was derived for the defined surface temperatures.

Discussion

Postoperative hypothermia after cardiac surgery remains a common problem[3–8,11] associated with inhibition of platelet function,[12] coagulation abnormalities,[13] increasing postoperative blood loss[14] and an increased need for transfusion of packed red cells.[8] Hypothermia may also trigger shivering and therefore increase myocardial and circulatory stress,[15] and can reduce resistance to surgical infections.[16] Postoperative hypothermia is also associated with prolonged mechanical ventilation, and prolonged intensive care unit and hospital length of stay.[8] Postoperative rewarming reduces shivering[11] and enables earlier extubation.[7]

Forced-air warming is a common method for rewarming after cardiac surgery. In 1994 Giesbrecht *et al.*[17] described significant differences between forced-air warming devices in combination with full body blankets. However, the clinical relevance of these results from a study of normothermic volunteers is uncertain, as the skin temperature of normothermic volunteers is generally higher than the mean skin temperatures of hypothermic postoperative cardiac surgical patients. Therefore, we investigated the heat transferring properties of 11 forced air warming systems with full body blankets using a validated copper manikin at temperatures reflective of the early postoperative setting. This manikin has been used previously for comparison of forced-air warming systems with upper[18] or lower body blankets.[19]

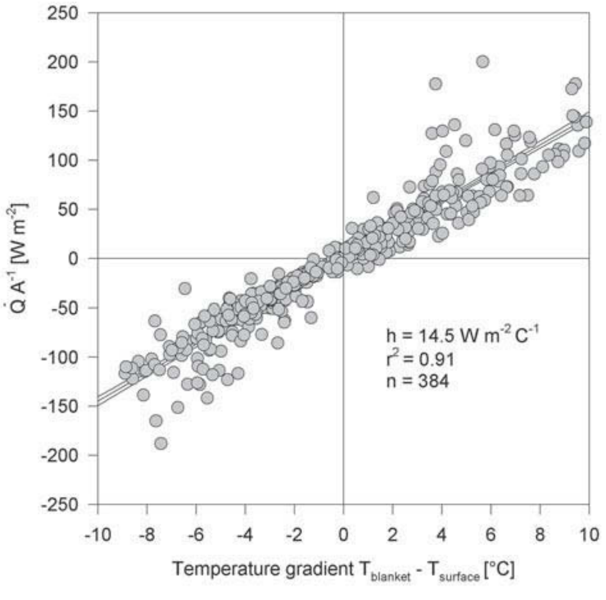

FIGURE 2 Determination of the heat exchange coefficient of the WarmTouch™ 5800 warming unit and MultiCover™ full body blanket. The heat exchange coefficient was calculated by linear regression analysis as the slope of heat exchange per unit area as a function of the blanket-surface temperature gradient. Regression line and 95% confidence intervals.

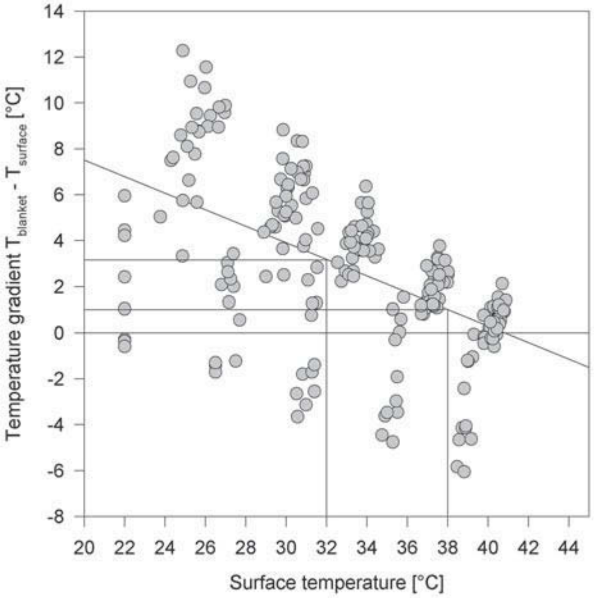

FIGURE 3 Determination of mean ΔT for the WarmTouch™ 5800 warming unit and MultiCover™ full body blanket. To calculate mean ΔT the temperature difference between the blanket and the manikin surface was plotted as a function of the temperature of the manikin surface and a regression line calculated to define their relationship. The equation of this regression line was used to derive mean ΔT for surface temperatures of 32°C and 38°C.

We found relevant differences in heat transfer between the different forced-air warming systems tested. Heat transfer ranged between 30.6 to 77.3 W for surface temperatures of 32°C, and between -8.8.to 29.6 W for surface temperatures of 38°C. This divergence in heat transfer at different surface temperatures is caused by the higher mean temperature gradient between the blanket and the manikin surface. This effect can be observed with every system, and limits heat transfer to an already warm surface temperature.

Three forced-air warming systems failed to maintain a positive temperature gradient between the blanket and the manikin surface at a surface temperature of 38°C and as a result, cooled the manikin. However, our results are at variance with those of Giesbrecht *et al.*[17] who found a heat transfer of 40 to 95 W. There are three possible explanations for the differences between their study and ours: 1) mean skin temperatures may not have been comparable; 2) our manikin may be limited in its ability to simulate realistic conditions for forced-air warming devices; and 3) forced-air warming systems have evolved during the 13-yr interval between these studies.

In the study of Giesbrecht *et al.* mean skin temperature under the forced-air warming system ranged between 36.5°C and 37.5°C.[17] In post-cardiac surgery patients[5,10] the mean skin temperature under a forced-air warming blanket rises slowly from 32°C to almost 38°C, and we have calculated heat transfer values to reflect the response at these surface temperatures. Therefore, the testing conditions of the studies were not comparable. However, as the temperature gradient between the blanket and the surface was higher at lower surface temperatures, we would have expected higher heat transfers in our study. When comparing the heat transfer values from our study at surface temperatures of 36°C to 38°C to the heat transfers observed by Giesbrecht *et al.*,[17] the difference becomes even greater. Here we can only see heat transfers from -8.8 to 44 W (Table II), which is much less than 40 to 95 W observed by Giesbrecht *et al.*[17] Accordingly, the different testing conditions cannot alone account for the different findings of these two studies.

The heat exchanging properties of this manikin model have been carefully validated.[20] The combined heat exchange coefficient for radiation and convection of the manikin is 11 $W \cdot m^{-2} \cdot °C^{-1}$. This corresponds well with the combined heat exchange coefficient for radiation and convection of 10.8 $W \cdot m^{-2} \cdot °C^{-1}$ that was measured previously in human volunteers using the same methodology.[20] The emissivity of the manikin is 0.96, whereas the emissivity of human skin is 0.98.[21] In a previous study in volunteers, we tested four different forced-air warming systems with upper body blankets[22] and demonstrated that we could confidently predict the heat transfer of these forced-air warmers with a previous investigation in manikins.[18] The heat transfer of three forced-air warming systems could be predicted exactly, whereas a fourth system was underestimated by 1.1 W, a value which is of minimal clinical importance. Therefore, the manikin is able to accurately simulate heat transfer of forced-air warming systems.

Discrepancies between studies may also reflect, to a certain degree, advances in the technology of forced-air warming systems which have taken place over the past decade. In the early 90's forced-air warming devices were used primarily for postoperative rewarming of conscious hypothermic patients. This application allowed for higher nozzle temperatures of the power units than today. In an unpublished series in 1994 we found that the Bair Hugger® 200 had a nozzle temperature of 51.3°C, the WarmAir® 133 power unit used a nozzle temperature of 45.0°C and the WarmTouch™ had a nozzle temperature of 48.8°C. The air flows of these earlier devices were also much higher than in the series of warming devices from the current investigation, where flow rates ranged between 17.4 $L \cdot sec^{-1}$ to 31.5 $L \cdot sec^{-1}$.

The increasing intraoperative use of forced-air warming systems has led to a reduction of nozzle temperatures, because there are reports of burns associated with the use of forced-air warming systems.[23] Another factor to consider is that most forced-air warming systems operate with a lower air flow in Europe compared to North America, because the AC power source in Europe uses 50 Hz, compared to 60 Hz in North America. The motors of most forced-air warming systems operate at reduced speed at 50 Hz, which decreases the air flow of the blower by approximately 20%. Only the motor of the Bair Hugger® Model 750 operates at the same speed at either 50 Hz or 60 Hz.

Finally, the higher nozzle temperatures and air flows from warming devices of the 1990s may explain why the heat transfer values in the investigation of Giesbrecht *et al.*[17] were higher than in our investigation, although Giesbrecht *et al.* did not report these data.

In conclusion, the evaluation of commercially available forced-air warming devices using a validated manikin model demonstrates clinically relevant differences between systems.

Several systems were unable to provide adequate heat transfer to the manikin at a surface temperature of 38°C.

Acknowledgement

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