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Application of heat flux transducers to determine perioperative heat exchange☆

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Abstract

Perioperative hypothermia is a common problem in anaesthesia. To maintain a constant body heat content it is necessary to achieve a steady state of metabolic heat production and external heat exchange. During anaesthesia and surgery this balance is disturbed. The heat production is decreased to a level below resting metabolic heat production while heat losses increase due to the surgical procedure. As a consequence, heat losses exceed metabolic heat production and patients get hypothermic.

Even during large abdominal operations the major source of heat loss (about 85%) is the radiative and convective heat loss from the skin. Because during anaesthesia heat production cannot participate in regulation, heat loss is of major importance. The four mechanisms of heat exchange are convection, conduction, radiation and evaporation. While evaporation is proportional to the difference of partial pressure of water vapour, the heat exchange by convection, conduction and radiation can be described as follows: $\dot{Q}\mathrm{A}^{-1} = h(T_{\mathrm{Skin}} - T_{\mathrm{Env}})$; $\dot{Q}$: heat flux (W), A: area (m^2); h: heat exchange coefficient (W m^{-2} °C^{-1}); T_{Skin}: skin temperature (°C); T_{Env}: environmental temperature (°C).

The driving force of heat exchange is the temperature difference. The heat exchange coefficient describes the efficacy of heat exchange for a given temperature difference. For operating room conditions the heat exchange coefficient for radiation and convection can be combined (h_{RC}).

To determine the heat exchange coefficient for a given heat exchange mechanism the temperature gradient (ΔT) between environment and skin has to be varied and the resulting heat flux per unit area (W m^{-2}) measured by heat flux transducers. The heat exchange coefficient can be determined by linear regression analysis as the slope of the heat flux per unit area versus the temperature gradient.

Several measures have been established to prevent perioperative hypothermia. Insulation reduces heat loss from skin about 30–80% depending on the material. Insulation reduces the h_{RC} and is described as $1/h_{\mathrm{RC}}$.

Heat transfer from the environment to the body can be achieved by active warming as forced air warming, conductive warming or radiative warming devices. The related heat flux is influenced by the h of each system, the temperature gradient between the skin and the blanket and the treated area. If the heat exchange coefficient is known, the heat exchange can be predicted by the measurement of the temperature gradient. This provides an estimation of intraoperative heat exchange, where heat flux measurement is difficult or impossible.

Keywords: Heat flux measurement; Perioperative; Heat exchange coefficient; Manikin

1. Introduction

Perioperative hypothermia is a common problem in anaesthesia. To maintain heat content of the body it is necessary to achieve equilibrium between metabolic heat production, external heat gain and heat losses. During anaesthesia and surgery this balance is disturbed. The heat production is de-

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creased to a level below the metabolic heat production in rest while the heat losses increase due to the surgical procedure. As a consequence, the heat losses exceed the metabolic heat production and patients get hypothermic. Additionally, redistribution of body heat after induction of anaesthesia [1] contributes to a decrease of core temperature.

Perioperative hypothermia impairs coagulation [2], causes higher blood losses [3,4], changes pharmacokinetics [5], causes postoperative shivering [6] with increased oxygen consumption [7], causes morbid cardiac events [8,9], wound infections [10] and prolongs hospital stay [10]. The physical principles of heat exchange and different measures to avoid hypothermia are reviewed in this paper.

2. Physical principles of heat transfer

The four mechanisms of heat exchange are convection, conduction, radiation and evaporation. While evaporation is proportional to the difference of partial pressure of water vapour, the heat exchange by convection, conduction and radiation can be simplified as follows: $\dot{Q}A^{-1} = h(T_{\mathrm{Skin}} - T_{\mathrm{Env}})$, where $\dot{Q}$: heat flux (W); A: area (m^2); h: heat exchange coefficient (W m^{-2} °C^{-1}); T_{Skin}: skin temperature (°C); T_{Env}: environmental temperature (°C).

The driving force of heat exchange is the temperature difference. The heat exchange coefficient is a value describing the efficacy of heat exchange. Physiological aspects as vasoconstriction or vasodilation are not influencing the heat exchange coefficient, but they influence heat exchange. Vasoconstriction lowers the skin temperature and therefore the temperature difference between the skin and the environment is lowered. Due to the lower temperature gradient heat flux is decreased. If the heat exchange coefficient is known, the heat loss can be predicted by the measurement of the temperature gradient.

3. Clinical implications

Even during large abdominal operations the major source of heat loss (about 85%) is the radiative and convective heat loss from the skin [11]. Therefore this heat loss is of great clinical importance.

For the determination of a heat exchange coefficient the temperature gradient (ΔT) between the skin and the environment has to be varied and the resulting heat flux per unit area (W m^{-2}) has to be measured with heat flux transducers. The heat exchange coefficient is then determined by linear regression analysis as the slope of the heat flux per unit area versus the temperature gradient (see Fig. 1).

The temperature gradient can be varied in trials using volunteers by changing the environmental temperature in a climate chamber. This is a complex procedure. For the determi-

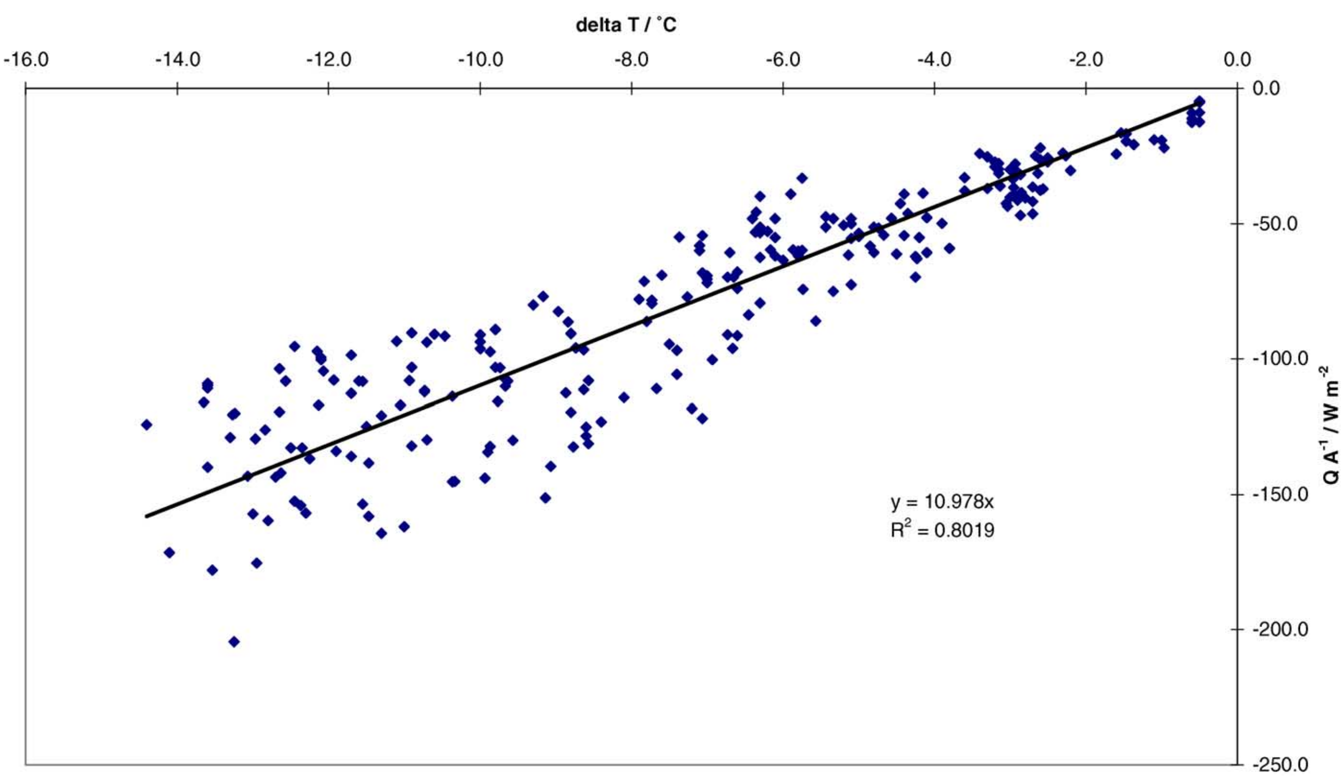

Fig. 1. h_{RC} of the manikin. Heat exchange coefficient of a validated copper manikin of the human body. The slope of the regression line represents the heat exchange coefficient. The environmental conditions were: room temperature 22 °C, air speed of <0.2 m s^{-1}, relative humidity between 40 and 50%. Modified from [12].

nation of the heat exchange coefficient we use an evaluated manikin [12], which allows us to change the surface temperature while environmental temperature remains constant.

4. Measurement of heat exchange

Heat exchange is measured with heat flux transducers. Heat flux transducers are used in thermal physiology and civil engineering, where thermal properties of buildings and materials are determined.

Heat flux transducers contain two thermopiles separated by a matrix with a fixed thermal resistance. When heat flows through a heat flux transducer the matrix causes a temperature gradient to develop between the two thermopiles. By the Seebeck effect, each thermopile generates a voltage proportional to its absolute temperature. The differential voltage between two thermopiles is proportional to the temperature gradient and therefore, since the thermal resistance of the matrix is fixed, to the heat flow through the heat flux transducer.

With heat flux transducers it is possible to measure heat gain or heat loss by radiation, convection and conduction. The evaporative heat loss cannot be measured with heat flux transducers, because the water vapour is not able to pass through the heat flux transducer. It is strongly recommended to calibrate heat flux transducers before using them because the calibration constants given by the manufacturer are often inappropriate.

The standard calibration method uses the Dynatech R-Matic Heat Flow Meter (Dynatech, Cambridge, MA, USA). The average accuracy of calibration is expected to be ±3%.

5. Measures to prevent hypothermia

Several measures have been established to prevent perioperative hypothermia. Insulation lowers heat loss from skin about 80% depending on the used material. Although insulation provides a reduction of heat loss, it is impossible to achieve heat gain by insulation. A heat transfer from the environment to the body can be achieved with active warming systems as forced air warming, conductive warming or radiative warming devices.

5.1. Insulation

Insulation reduces heat losses from the surface of the body. This can be described as a reduction of h_{RC}. Insulation can be quantified as the reciprocal value of heat exchange coefficient ($1/h_{RC}$). The SI units of insulation are $m^2\,°C\,W^{-1}$. In clothing industry the unit "Clo" is usual (1 Clo = 0.155 $m^2\,°C\,W^{-1}$).

The heat exchange coefficient for a minimally closed person exposed to air (air speed < 0.2 $m\,s^{-1}$, humidity 40–50%) is 10.1 $W\,m^{-2}\,°C^{-1}$. This heat exchange coefficient describes the heat exchange of the body exposed to the surrounding air. Its reciprocal value is the insulation of the body by the surrounding air (I_{Air}: ($1/h_{RC} \times 6.45$) = 0.64 Clo). The insulation of air is always present, as there is air surrounding the body. The effect of an insulating material is added to the insulation of air. The total insulation (I_{Tot}) is a sum of the insulation by the surrounding air (I_{Air}) and the insulation of the material (I_{Mat}). Fig. 2 shows the relationship between the h_{RC} and total insulation (in Clo). The relationship between these two parameters can be described as a hyperbolic curve (h_{RC} = 6.45

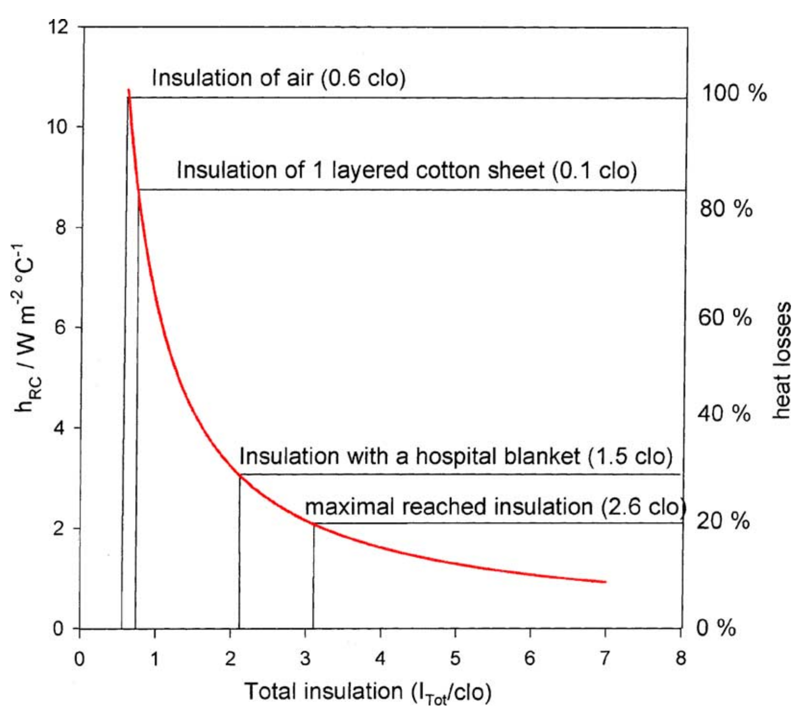

Fig. 2. h_{RC} insulation, modified from [13]. Heat exchange coefficient vs. total insulation ($I_{Air} + I_{Mat}$). $h_{RC} = I_{Tot} \times 6.45$.

Table 1
Clo values of several materials (modified from [13])

Insulation material	Clo
Surrounding air (I_{Air})	0.64
Garbage bag	0.01
Cotton sheet	0.1
Thin cotton blanket	0.2
Disposable surgical drape	0.2
Clothing of surgeon	0.6
Thinsulate CS 100 (1 cm polyester wool)	0.9
Thinsulate CS 200 (2 cm polyester wool)	1.4
Thinsulate US 200 (3M)	1.8
Thinsulate THL 3 (3M)	2.0

$\times\ I_{Tot}{}^{-1}$). It is obvious that even little insulation added to the insulation of air causes a relevant reduction of h_{RC}. With acceptable efforts an insulation of about 2.5 Clo is possible. A further increase in insulation causes only little change in h_{RC}. This function is asymptotic. It is impossible, that heat losses are reduced to zero by insulation.

Several materials, which are in use in operation theatre, have been tested for their insulating characteristics [13] (see Table 1). Insulating materials used in the perioperative course reach Clo values from 0.1 (cotton sheet) to 0.6 Clo (clothing of surgeon). Only the hospital blanket shows an insulation of 1.9 or 3.4 Clo if double layered (unpublished data). The h_{RC} is reduced to 3.4 or 1.9 W m^{-2} °C^{-1}, respectively.

A calculation demonstrates the clinical implication of these values. If the metabolic heat production is 60 W m^{-2}, the heat loss from the skin is assumed to be 85%, a thermal comfort skin temperature is 34 °C and the air temperature is 20 °C, then the insulation required to maintain the body heat is $(34 - 20)/(60 \times 0.85) = 0.27$ m^2 °C W^{-1} = 1.77 Clo. With an insulation of air (0.64 Clo) the insulation of the material required to maintain body heat content is 1.13 Clo. In daily life several materials provide an insulation in this range and allow outdoor activities. In operation theatre only few materials reach an insulation of more than 0.6 Clo. With insulating materials like this, it is impossible to balance heat losses and heat gain in the operating theatre. If the thermal protection has to be performed mainly with insulating materials, these materials have to be selected more carefully.

Insulating materials can be divided into two categories. There are insulating materials working by dead air in a closed system, and reflective materials. Dead air has good insulating qualities (I_{Mat}: 1.76 Clo cm^{-1}) [14]. If the system is open at its periphery to the environment, the insulation (I_{Mat}) provided by 1 cm air is reduced to only 0.28 Clo cm^{-1}. It is obvious that multiple layers of an insulation material working with dead air can enhance efficacy.

The second group of insulating materials are reflective materials. These insulating materials reduce the emitted radiation by reflection. The reflection can be optimised by finding the best distance between the body and the reflective material. If the distance is reduced to zero heat transfer mechanism is conduction and no longer radiation. If the distance is too far, heat loss by convective air movement between the surface and the insulator appears. The reflection on its own cannot be increased by making multiple layers.

5.2. *Forced air warming*

The most common active warming devices in the perioperative course are forced air warming systems. A power unit provides a warm air stream, which is connected by a hose to a warming blanket. For several intraoperative approaches different designed blankets are available. For abdominal surgery upper body blankets or lower body blankets are suitable.

Table 2
Heat exchange coefficients, mean temperature gradients at surface temperature of 36 (ΔT at 36 °C) and 38 °C (ΔT at 38 °C) and the resulting heat exchange between the upper body blanket and the surface of a validated manikin

System	h (W m^{-2} °C^{-1})	ΔT at 36 °C (°C)	ΔT at 38 °C (°C)	Heat exchange at 36–38 °C (W)
Bair Hugger®	27.2	1.37	0.51	13.0–4.9
ThermaCare®	28.8	1.88	1.14	19.0–11.5
ThermaCare®—Optisan®	25.0	2.26	1.28	19.8–11.2
WarmAir®	17.7	2.02	1.14	12.5–7.1
WarmGuard®	15.1	0.75	0.49	4–2.6
WarmGuard®—reusable	20.4	2.46	1.58	17.6–11.3
WarmTouch®	36.2	2.10	1.43	18.1–26.6
WarmTouch®—reusable	22.1	3.31	2.28	17.6–25.6

Table 3
Heat exchange coefficients, mean temperature gradients at surface temperature of 36 (ΔT at 36 °C) and 38 °C (ΔT at 38 °C) and the resulting heat exchange between the lower body blanket and the surface of a validated manikin

System	h (W m^{-2} °C^{-1})	ΔT at 36 °C (°C)	ΔT at 38 °C (°C)	Heat exchange at 36–38 °C (W)
Bair Hugger®	26.0	1.24	0.62	8.7–17.4
ThermaCare®	24.5	1.38	0.63	8.3–18.3
WarmAir®	14.4	2.15	1.08	8.4–16.7
WarmGuard®	12.5	1.99	1.19	8.0–13.4
WarmGuard®—reusable	13.1	2.48	1.63	11.5–17.5
WarmTouch®	30.8	1.04	0.50	8.3–17.3

Postoperatively full body blankets are favourable. Following the equation $Q^{\cdot} = h_{RC}(T_{Skin} - T_{Blanket})A$, the heat flux is influenced by the h_{RC} of each system, the temperature gradient between the skin and the blanket and the treated area.

We evaluated several forced air warming systems (see Tables 2 and 3). For upper body blankets h_{RC} values from 15.1 to 36.2 W m^{-2} °C^{-1} were described [15]. For lower body blankets the h_{RC} ranged from 12.5 to 30.8 W m^{-2} °C^{-1} [16]. The h_{RC} is influenced by the air flow provided by the power unit but mainly by the architecture of the blanket [17] (see Fig. 3). The temperature gradient between the blanket and the skin is limited, as a high blanket temperature may cause thermal burns [18]. The skin temperature under forced air warming reaches about 36–38 °C. The resulting temperature gradient under a forced air warming blanket is about 2 °C.

The third factor contribution to heat transfer is the covered area. This area can be estimated to be about 0.35 m^2 for an upper body blanket, 0.54 m^2 for a lower body blanket and 1.21 m^2 for a full body blanket. The resulting heat transfer at a surface temperature from 36 and 38 °C for an upper body blanket varies from 2.6 to 26.6 W [15]. With lower body warming, the heat transfer ranges between 8.0 and 18.3 W [16]. The heat transfer under full body forced air warming ranges from −8.8 to 44 W.

In most clinical comparisons of forced air warming devices with other active warming devices forced air warming is superior [19]. The explanation is that forced air warming treats the room facing skin. This part of the body is no longer an important area of heat loss but is turned to an area of heat gain. With conductive heating of the back, the change in heat balance is smaller, because the treated area shows only small conductive heat loss without warming. If conductive heating is applied to the room facing surface, there is no relevant difference to forced air warming [20]. The net heat loss + heat gain for forced air warming is shown in Fig. 4.

5.3. Conductive warming

Conductive heat transfer can be achieved with electrical heating mattresses or heated water mattresses. These warming devices can be applied under the back or like forced air warming systems covering the room facing skin. The heat exchange coefficient for conduction (h_K) is with optimal contact about 40 W m^{-2} °C^{-1} and therefore higher than with forced air warming systems.

In case of covering the room facing skin with a conductive heating device, the h_K will not reach the theoretical value of 40 W m^{-2} °C^{-1} because it is impossible to obtain a perfect contact to the skin. As air trapping is unavoid-

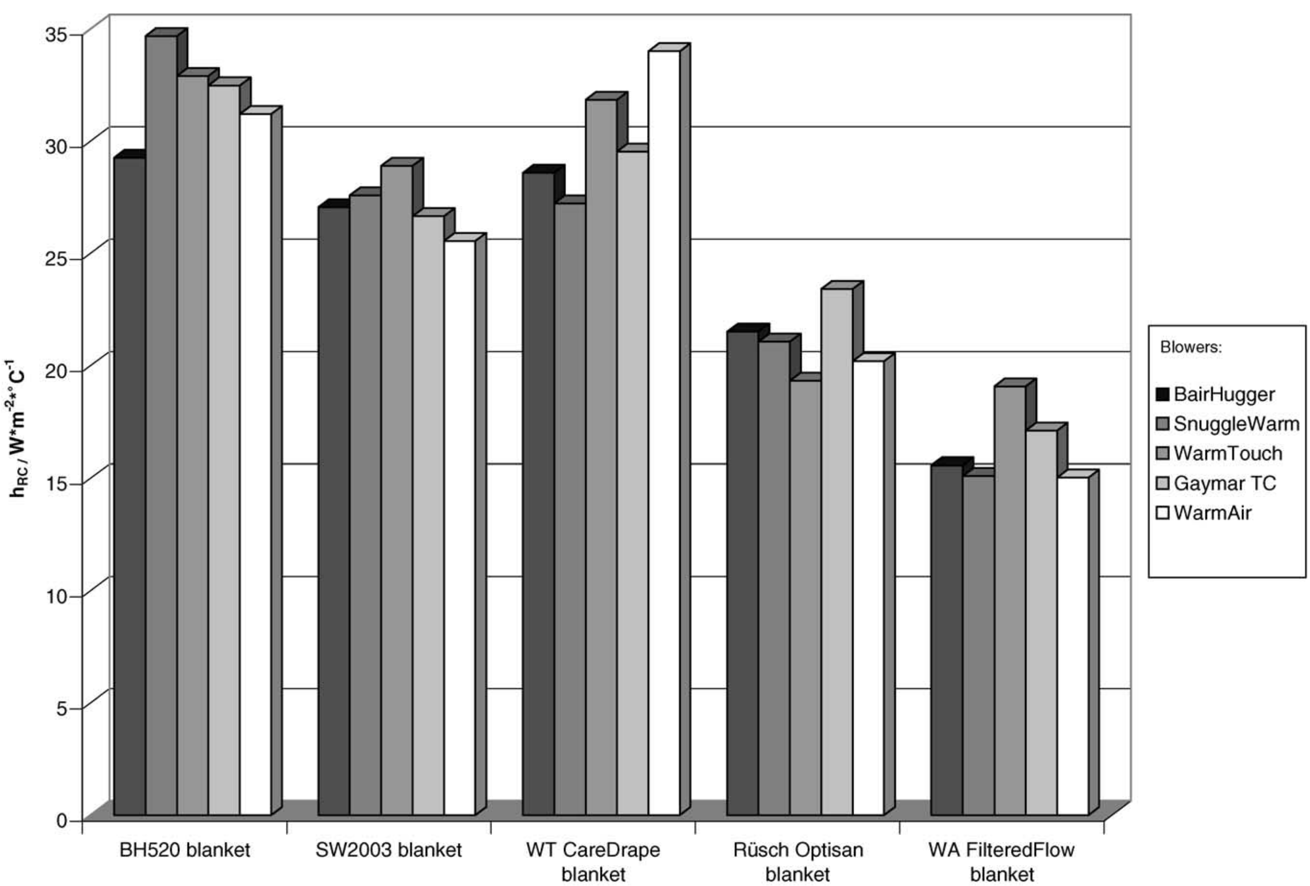

Fig. 3. h_{RC} of different upper body blankets in combination with different blower units [17].

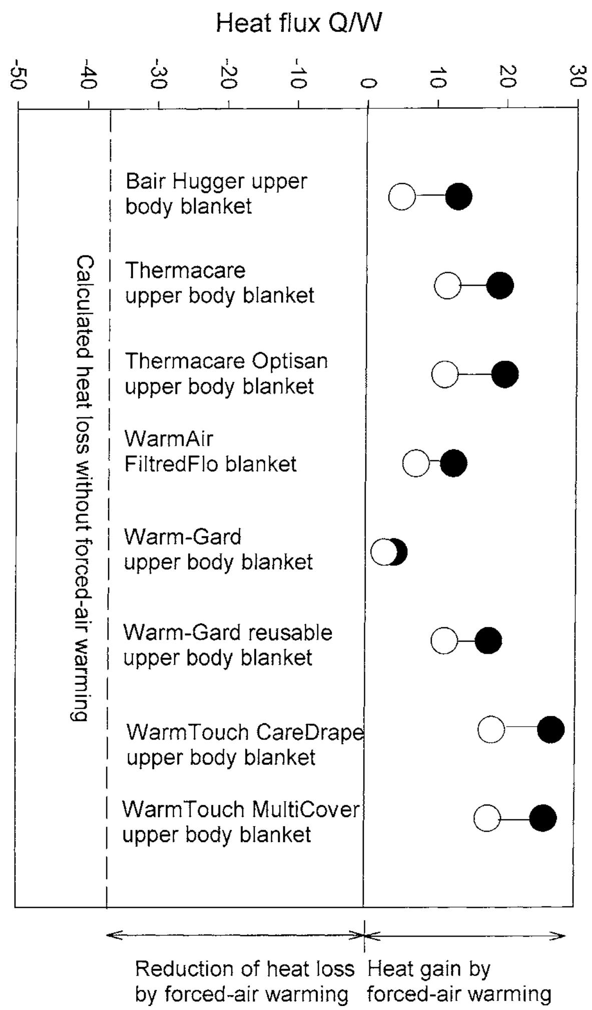

Fig. 4. Heat loss + heat gain forced air warming, modified from [15].

able, the heat exchange mechanism will change from conduction to a mixture of conduction, convection and radiation. The estimated heat exchange coefficient is then only about $20\,\mathrm{W\,m^{-2}\,{}^{\circ}C^{-1}}$.

5.4. Radiative warming

As radiative warming devices are low-temperature thermal ceilings common. These devices provide a homogenous heat distribution. The application in intraoperative use is limited because of a relative high space requirement. The thermal strain for the operation team is a second limiting factor. Effective radiative warming is only possible, if the treated skin is not insulated by any coverings.

Radiative warming devices provide a relatively low heat exchange coefficient. The efficacy of radiative heaters is caused by the large temperature gradient, which can reach 30–60 °C.

6. Conclusions

During anaesthesia and surgery an imbalance of metabolic heat production and heat loss is responsible for a decrease of body heat content. To avoid perioperative hypothermia an understanding of physical principles of heat exchange is necessary. To estimate the efficacy of different approaches to maintain normothermia, the heat exchange coefficient is the basis of calculation of intraoperative heat exchange. The heat exchange coefficient is determined by the use of heat flux transducers. If the heat exchange coefficient is known, the heat exchange can be calculated by measurement of temperature differences.

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