Cutaneous heat loss in children during anaesthesia

H. Anttonen, K. Puhakka, J. Niskanen and P. Ryhänen

Summary
We have measured non-evaporative, cutaneous heat loss using heat flux transducers at eight skin sites in five children during anaesthesia and compared the data with basal metabolic heat production. The effect of disposable surgical covering and a radiant heater on heat flux was examined. The mean total heat flow rate before draping was 3.9 W higher than the basal metabolic rate after induction of anaesthesia with a simultaneous decrease in rectal temperature. Mean cutaneous heat loss was 62 (SD 9) W m⁻² (9.5 (2.1) kJ kg⁻¹ h⁻¹) in children older than 1 yr and 84 W m⁻² (17.2 kJ kg⁻¹ h⁻¹) in a 3-month-old infant. Disposable drapes diminished cutaneous heat loss by 29% and a radiant heater by 77%. Heat conduction to the mattress was 21 (7) W m⁻². These results showed that the decrease in core temperature after induction of anaesthesia was genuine cooling, that is heat loss exceeded heat production. (Br. J. Anaesth. 1995; 74: 306-310)

Key words
Anaesthesia, paediatric Temperature, monitoring. Skin, temperature.

Heat production in infants and children during anaesthesia has been reported to be similar to basal metabolic rate [1, 2]. During anaesthesia heat exchange between the skin and environment occurs passively as thermoregulatory responses are absent in both children and adults until core temperature is 34–35 °C [3–6]. Hypothermia results when heat loss exceeds heat production.

Dry cutaneous heat loss can be measured directly with heat flux transducers (HFT) and values are in good agreement with those obtained by calorimetry [7]. In adult volunteers lying prone on an operating table, heat exchange between skin and the environment has been determined using this method and found to be 9.7 W m⁻² °C⁻¹ [8]. During isoflurane anaesthesia in adults, cutaneous heat loss of 125 W was measured using the same method [9, 10]. No similar study has been performed in children.

We postulated that if thermal balance is maintained (= constant core temperature) heat loss should not exceed basal metabolic heat production in children during anaesthesia. We therefore measured total dry cutaneous heat loss using HFT and compared the values obtained with basal metabolic heat production in five anaesthetized children. The effects of a disposable perioperative covering and a radiant heater on heat loss were also evaluated.

Patients and methods
Five children, ASA I or II, undergoing surgery with general anaesthesia were examined, after approval of the Ethics Committee of Oulu University and informed consent from their parents. The diagnoses and surgical procedures performed were as follows: oesophagoscopy and dilatation after operated oesophageal atresia (patient No. 1), extirpation of a lower back haemangioma (patient No. 2), removal of a Kirschner pin from an operated congenital dislocation of the hip (patient No. 3), open reduction of a supracondylar fracture of the left humerus (patient No. 4) and cholecystectomy for gallstones (patient No. 5). The clinical details of the patients are presented in table 1.

Heat fluxes at eight skin sites, surface temperatures at 15 sites (fig. 1) and rectal temperature were recorded with a computer-controlled measuring system comprising a HP 216 computer and a HP 3421 data logger (Hewlett-Packard Inc., Palo Alto, CA, USA) every 2 min during anaesthesia and operation. The recordings were begun after induction of anaesthesia as soon as all transducers were attached correctly to the skin and were discontinued at the end of anaesthesia when the patient began moving.

Heat loss (W m⁻²) was measured using HA-13-18-10-P(C) thermal flux transducers (Thermonetics Co., San Diego, CA, USA). The transducer measures total heat loss (or gain) via radiation, conduction and convection, but does not detect evaporative loss. The transducers are circular discs, 25 mm in di-

Table 1

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Age (yr)</th>
<th>Weight (kg)</th>
<th>Body surface area (m²)</th>
<th>Posture</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.25</td>
<td>4.6</td>
<td>0.26</td>
<td>Supine</td>
</tr>
<tr>
<td>2</td>
<td>2.33</td>
<td>11.5</td>
<td>0.52</td>
<td>Prone</td>
</tr>
<tr>
<td>3</td>
<td>4.00</td>
<td>14.5</td>
<td>0.67</td>
<td>Supine</td>
</tr>
<tr>
<td>4</td>
<td>3.75</td>
<td>18.0</td>
<td>0.76</td>
<td>Prone</td>
</tr>
<tr>
<td>5</td>
<td>7.67</td>
<td>26</td>
<td>0.96</td>
<td>Supine</td>
</tr>
</tbody>
</table>

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Figure 1 Placement of the eight heat flux transducers, HF₁–HF₈ (○) and the 15 skin temperature sensors, $T₁$–$T₁₅$.

ameter and 2 mm in depth, and were attached carefully to clean, dry skin surfaces using glue. The transducers contain two multi-junction thermopiles separated by a fixed thermal resistance, and when placed on a warm surface the thermopile in contact with the surface warms up while the other remains cool.

By a thermoelectric effect, each thermopile generates a voltage proportional to its temperature and thus the voltage differential between the thermopiles is proportional to the temperature gradient. Therefore, as there is a fixed thermal resistance to heat flow through the transducer, the transducer constant is 100 W m⁻² mV⁻¹. Thermal resistance for a heat flux sensor is 0.006 m² K W⁻¹ and with a low air velocity thermal resistance of bare skin may be 0.07 m² K W⁻¹. The manufacturer has reported the precision of these sensors as ±10%. Each of the 12 transducers were also calibrated by the investigators with a guarded hot plate [11] in a climate chamber producing unidirectional heat flux, and they showed a mean error of less than ±5% from the value given by the manufacturer. The error in the voltage measurements of the sensors produced an error of 1 W m⁻² in heat flux (±2% on average). The error caused by the sensor itself was thus less than ±3% on clothed sites and less than ±8% on bare skin, that is less than ±4% in such measurements [12, 13]. Hence, including calibration and measurement errors, the maximum error of mean heat flux measured at eight sites was less than ±7%.

Thermal sensors were types 409 and 427 of the YSI-400 series (Yellow Springs, OH, USA), with a precision of ±0.1°C. The skin temperature sensors were attached firmly with a 1.5-cm square piece of plaster tape.

All patients were naked after induction of anaesthesia and while the surgical area was being prepared. Four patients were then covered in a manner customary for each operation with a disposable drape (Klinidrape, Mölnlycke; Sweden). One infant was uncovered throughout the operation, and after rectal temperature had decreased to less than 36 °C, a 660-W radiant heater (Ohio nc, Ohio Medical Products; Madison, WI, USA) was placed over the infant. The head was always uncovered. Patients lay on the operating table in either the prone or supine position and the table was covered with a foam mattress with no external heating.

Thermal conditions in the operating theatre (humidity, temperature, air velocity and thermal radiation) were standardized using an indoor climate analyser (B & K 1213, Brüel & Kjær Inc., Naerum, Denmark).

Premedication comprised glycopyrronium 5 µg kg⁻¹ i.m. (<10 kg) or rectal diazepam 0.5 mg kg⁻¹ and pethidine 1.5 mg kg⁻¹ (10–20 kg) or oral flunitrazepam 1.5 mg (>20 kg). Anaesthesia was induced with thiopentone 5 mg kg⁻¹ i.v. or rectal methohexitone 20 mg kg⁻¹ and fentanyl 2 µg kg⁻¹ i.v., with additional doses of thiopentone 1–2 mg kg⁻¹ and fentanyl 1–2 µg kg⁻¹ as needed. The trachea was intubated after administration of alcuronium 0.3 mg kg⁻¹ i.v. and neuromuscular block maintained with alcuronium 0.1 mg kg⁻¹ i.v. Heart rate, arterial pressure (non-invasive), oxygen saturation and train-of-four nerve stimulation were monitored.

The patients’ lungs were ventilated mechanically with a volume-controlled ventilator (Servo 900 C, Elema Schönander Inc., Stockholm, Sweden) using 70% nitrous oxide in oxygen, and ventilatory
frequency and tidal volume (≈ 10 ml kg⁻¹) were adjusted to maintain end-tidal PCO₂ at 4.5 kPa. A Humid Vent I or Humid Vent Mini (Gibeck Respiration Inc., Upplands Väsbys, Sweden) was used for airway humidification and heat and moisture exchange.

Both the maintenance fluid, Ringer's acetate with 5% glucose 4 ml kg⁻¹ h⁻¹, and the volume substitution fluids for operative bleeding were infused during operation via a blood warmer (Horstmann-Brasswill Works Inc., Bath, England).

**Table 2** Weighting coefficients (c_\text{f}) according to the proportions of the body regions, c_\text{f}, for heat flux calculations. The placement of respective heat flux and temperature sensors is shown in figure 1.

<table>
<thead>
<tr>
<th>Area</th>
<th>c_\text{f,1.2.3}</th>
<th>c_\text{f,4.5}</th>
<th>c_\text{f,6.7}</th>
<th>c_\text{f,8}</th>
<th>c_\text{f,9}</th>
<th>c_\text{f,10}</th>
<th>c_\text{f,11.12}</th>
<th>c_\text{f,13.14}</th>
<th>c_\text{f,15}</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1 yr</td>
<td>0.19</td>
<td>0.20</td>
<td>0.20</td>
<td>0.28</td>
<td>0.08</td>
<td>0.06</td>
<td>0.11</td>
<td>0.10</td>
<td>0.07</td>
</tr>
<tr>
<td>1-4 yr</td>
<td>0.17</td>
<td>0.19</td>
<td>0.19</td>
<td>0.30</td>
<td>0.08</td>
<td>0.06</td>
<td>0.13</td>
<td>0.10</td>
<td>0.07</td>
</tr>
<tr>
<td>5-9 yr</td>
<td>0.13</td>
<td>0.14</td>
<td>0.20</td>
<td>0.34</td>
<td>0.08</td>
<td>0.06</td>
<td>0.15</td>
<td>0.11</td>
<td>0.07</td>
</tr>
</tbody>
</table>

Mean (SD) values were determined for the variables and mathematical processing of the data was via the SAS program (SAS Institute Inc., Cary, NC, USA).

Total cutaneous heat loss (THF, W) was calculated by multiplying mean cutaneous heat loss (HF_m, W m⁻²) by body surface area (BSA) for each measurement:

\[
\text{THF (W)} = \text{HF}_m \times \text{BSA}
\]

\[
\text{HF}_m (W m^{-2}) = (c_{\text{head}} \times \text{HF}_1 + c_{\text{ext. trunk}} \times (\text{HF}_2 + \text{HF}_3) / 2 + c_{\text{post. trunk}} \times (\text{HF}_4 + \text{HF}_5) / 2 + c_{\text{up. extrem.}} \times (\text{HF}_6 + \text{HF}_7) / 2)
\]

HF_m was calculated as the sum of the area-weighted mean heat fluxes. The weighting coefficients (c_\text{f}) are expressions of each body region as a proportion of the total body surface area and were taken from the tables published by Lund and Browder in 1944 for children of various ages (table 2) [14]. The mean values for THF and HF_m were calculated from measurements obtained when the child was uncovered and when draped or under a radiant heater. The results were expressed also in kJ kg⁻¹ h⁻¹ (1 W = 3.6 kJ h⁻¹).

Mean regional heat flux (HF_r, W m⁻²) and respective mean regional skin temperatures (T_m) of the eight body regions were calculated from the transducer measurements (HF_r, HF_m, fig. 1) for each patient lying uncovered at ambient room temperature (T_amb). Basal metabolic rate (BMR) was obtained for each patient from the tables of Talbot [15] according to weight and sex in kcal per day and expressed in W, W m⁻², and kJ kg⁻¹ h⁻¹.

An area-weighted, age-adjusted 15-site mean skin temperature (T_m) was calculated from the temperatures measured at all 15 sites (fig. 1) according to the following equation [16, 17]. The weighting coefficients (c_\text{f,T}) are shown in table 2.

\[
T_{\text{m}15} = c_{\text{head}} \cdot (T_1 + T_2 + T_3) / 3 + c_{\text{ext. trunk}} \cdot (T_4 + T_5) / 2 + c_{\text{post. trunk}} \cdot (T_6 + T_7) / 2 + c_{\text{up. extrem.}} \cdot T_8
\]

\[
+ c_{\text{hand}} \cdot T_9 + c_{\text{t. extrem.}} \cdot (T_{10} + T_{12}) / 2 + c_{\text{leg}} \cdot (T_{11} + T_{14}) / 2 + c_{\text{foot}} \cdot T_{15}
\]

**Results**

Operating room temperature was 22.0 (1.1) °C, relative humidity 31 (3)%, air velocity 0.11 (0.03) m s⁻¹ and radiation 445 (9) W m⁻². Radiation under the operating table lights varied from 452 to 672 W m⁻².

The mean total heat flow rate was higher than BMR before draping in all cases; the difference varied from 3 to 9 W. THF values were lower than BMR after draping or under a radiant heater (fig. 2). The time courses of rectal and 15-site mean skin temperatures for each patient are shown in figures 3 and 4. Rectal temperature decreased in all patient after induction of anaesthesia.

Mean cutaneous heat loss (HF_m) in children more than 1 yr of age was 62 (9) W m⁻² (9.5 (2.1) kJ kg⁻¹ h⁻¹) on the operating table without drapes. The disposable drapes diminished HF_m to 44 (5) W m⁻² (6.8 (1.3) kJ kg⁻¹ h⁻¹) (29%). HF_m for the uncovered infant was 84 W m⁻² (17.2 kJ kg⁻¹ h⁻¹) and under a radiant heater 20 W m⁻².
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Mean BMR for children older than 1 yr was 53 (4) W m⁻² (8.1 (1.2) kJ kg⁻¹ h⁻¹) and for the 4.6-kg infant, 50 W m⁻² (10.2 kJ kg⁻¹ h⁻¹).

Forhead heat flux was highest in all children with a mean value for all patients of 107 (18) W m⁻². Mean HF from all body regions in contact with the mattress was 21 (7) W m⁻². Regional heat fluxes from bare skin areas before draping are plotted against the temperature difference between the skin and operating room in figure 5.

Discussion

We found that non-evaporative cutaneous heat loss exceeded basal metabolic heat production after induction of anaesthesia when patients were uncovered. In this study the anaesthetic comprised a barbiturate, opioids and neuromuscular blockers, and in dogs barbiturates reduce resting metabolic rate by 10 % [18]. Hence metabolic rate in this study was lower than BMR and the difference between heat loss and heat production was even greater. Heat production in children during halothane anaesthesia has been reported to be 10.0±2.9 kJ kg⁻¹ h⁻¹ in infants aged 1 yr or less and 8.4±1.3 kJ kg⁻¹ h⁻¹ in older children, that is similar to BMR [2]. Metabolic rate was not measured here because an uncuffed tracheal tube was used. Total heat loss exceeds the measured non-evaporative cutaneous heat loss alone if evaporation via the skin and respiratory tract are taken into account. The observed decrease in rectal temperature after induction of anaesthesia reflected excessive heat loss.

Thermal radiation is the main mechanism for heat loss under physiological conditions, while evaporation, convection and conduction are less important. In a calorimeter with a temperature of 27.4 °C and a relative humidity of 25 %, radiation made up 58 % of total heat loss, evaporation 27 % and convection and conduction 15 % [17]. Heat loss from bare skin areas depends on the temperature difference between the skin and the environment. The highest regional heat fluxes in this study were observed in the forehead (107 (18) W m⁻²). The relationship between regional heat flux and temperature difference was exponential and this can be explained by increasing radiation, as radiant heat transport is dependent on temperature to the fourth power [17]. Conductive heat loss via regions facing the mattress was uniform in all patients (21 (7) W m⁻²). Thus even though nearly 50 % of the body surface area was in contact with the mattress in the supine–prone positions, conductive heat loss from the body to the mattress was less important than radiant and convective heat loss to the operating theatre air.

The heat flux method used here for the first time in children demonstrated the effects of insulation and external heating rapidly. The quantity of heat loss cannot be determined from skin temperature measurements alone as it depends on the temperature
gradient between skin and the contact surface and on the material with which the skin is in contact (e.g. air, surgical drape, mattress). The most important factor in reducing heat loss from the skin during surgery and in preventing hypothermia is insulation by drapes [19]. The insulative properties of various materials can be determined using clo values (1 clo = 0.155 °C m² W⁻¹) [20]. Insulation (I) can be calculated from the formula [21]: I = Tₐ - Tₘₐₜ/(cutaneous heat loss). For example, if, as in these cases, the temperature difference between skin and room air is 10 °C and the allowed heat loss of the child is 50 W m⁻², a thermal resistance of more than 0.2 °C m² W⁻¹ (1.3 clo) is needed to maintain thermal balance.

During anaesthesia the decrease in core temperature has been explained by redistribution of body heat via transfer from the core to the body surface, allowing the surface temperature to increase while the core temperature decreases [22]. Based on the results in the present study it can be concluded that cutaneous heat loss exceeded basal metabolic heat production after induction of anaesthesia. Hence the decrease in core temperature during anaesthesia was not simply a product of heat redistribution but rather a sign of imbalance between heat production and heat loss. Therefore, heat loss can be counteracted effectively by external heating in the operating room.

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References