Calculation of mean skin temperature and changes in body heat content during paediatric anaesthesia


SUMMARY

Mean skin temperature and changes in body heat content were calculated in several different ways from measurements made in five children during operation. Mean skin temperatures were calculated from 162 sets of measurements using 15, 12, eight, seven and four skin sites with various formulae modified according to age. The results of other formulae were compared with age-adjusted, area-weighted 15-site mean skin temperature which was used as a reference. Changes in body heat content were calculated from Burton's equation in different ways and errors from different variables in the formula were evaluated. Mean skin temperature from 12 skin sites was within 0.5 °C of the 15-point reference method, and that from four sites within 1 °C. The core temperature selected and the weighting coefficients used in calculating mean body temperature were more important sources of error in the determination of change in body heat content than was mean skin temperature. (Br. J. Anaesth. 1994; 72: 548–553)

KEY WORDS

Investigation of heat loss during anaesthesia has estimated the change in body heat content from measurements of body mass, mean skin temperature and core temperature [1–4]. Mean skin temperature is calculated from spot measurements at several sites, which are weighted by various methods [5–11]. In children, there have been many studies of temperature regulation but no physiological or clinical studies on the calculation of mean skin temperature and body heat content. The relative size of surface regions varies with age [12, 13] and therefore the use of adult weighting coefficients is not appropriate in children.

The aim of this study was to develop a suitable method for calculation of mean skin temperature in paediatric studies of heat loss. The formulae were chosen to correspond with methods used in adults, published previously [4–11], with a minimum number (at least four) of skin sites. Another aim of the study was to assess the errors in the calculation of body heat content which might occur from different variables used in the equation.

PATIENTS AND METHODS

With the approval of the Ethics Committee of Oulu University and informed consent from the parents of each patient, we studied five paediatric patients, ASA I or II, undergoing surgery under general anaesthesia.

Skin temperatures were measured at 15 sites ($T_i - T_{15}$), recommended by Winslow, Herrington and Gagge [5]. The temperature sensors were always placed on the same sites on skin areas of the forehead ($T_f$), cheek ($T_c$), occiput ($T_o$), chest ($T_t$), abdomen ($T_a$), shoulder ($T_s$), back ($T_b$), upper arm ($T_u$), lower arm ($T_l$), back of the hand ($T_h$), forehead ($T_f$), posterior thigh ($T_{th}$), shin ($T_{sh}$), calf ($T_{ca}$) and dorsal foot ($T_{df}$), according to figure 1.

Thermal sensors were types 409 and 427 of the YSI-400 series (Yellow Springs Inc, U.S.A.), round, with a thickness of 2 mm and a diameter of 5 mm. They were attached firmly with a 1.5-cm square piece of plaster tape. An oesophageal temperature probe was placed in the lower third of the oesophagus and a rectal probe 3–5 cm above the anus, depending on the size of the patient. The precision of the sensors was ±0.1 °C and the maximum measurement error was ±0.2 °C. Temperature measurements were performed by a computer controlled measuring system (HP 216-computer, HP 3421-datalogger, Hewlett–Packard Inc, CA, U.S.A.) every 2 min. The recording was begun during induction when the patient became motionless and was discontinued at the end of anaesthesia when the patient started moving. The thermal conditions in the operating theatre (humidity, temperature and air velocity) were measured with an indoor climate analyser (B & K 1213, Brüel & Kjær Inc, Copenhagen) and these results and clinical details of the patients are presented in table I.

Premedication comprised glycopyrronium 5 µg kg⁻¹ i.m. if patients weighed less than 10 kg, rectal diazepam 0.5 mg kg⁻¹ and pethidine 1.5 mg kg⁻¹ if they weighed between 10 and 20 kg and oral
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**FIG. 1.** Placement of the 15 skin temperature sensors, $T_1-T_{15}$.

### TABLE I. Patient characteristics and thermal conditions in the operating room. BSA = Body surface area; Temp. = room temperature; RH = relative humidity; $v$ = air velocity

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Age (yr)</th>
<th>Weight (kg)</th>
<th>BSA (m$^2$)</th>
<th>Time (h)</th>
<th>Posture</th>
<th>Diagnosis and procedure</th>
<th>Temp. (°C)</th>
<th>RH (%)</th>
<th>$v$ (m s$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.67</td>
<td>26</td>
<td>0.96</td>
<td>1.27</td>
<td>Supine</td>
<td>Gallstones</td>
<td>22.1</td>
<td>33</td>
<td>0.07</td>
</tr>
<tr>
<td>2</td>
<td>3.75</td>
<td>18.0</td>
<td>0.76</td>
<td>2.43</td>
<td>Prone</td>
<td>Cholecystectomy</td>
<td>23.1</td>
<td>34</td>
<td>0.12</td>
</tr>
<tr>
<td>3</td>
<td>4.00</td>
<td>14.5</td>
<td>0.67</td>
<td>0.57</td>
<td>Supine</td>
<td>Supracondylar fracture of the left humerus. Open reduction</td>
<td>22.9</td>
<td>31</td>
<td>0.10</td>
</tr>
<tr>
<td>4</td>
<td>2.33</td>
<td>11.5</td>
<td>0.52</td>
<td>1.30</td>
<td>Prone</td>
<td>Congenital dislocation of the hip. Removal of Kirschner pin Haemangiona of the low back. Extirpation</td>
<td>20.4</td>
<td>31</td>
<td>0.14</td>
</tr>
<tr>
<td>5</td>
<td>0.25</td>
<td>4.6</td>
<td>0.26</td>
<td>0.43</td>
<td>Supine</td>
<td>Haemangiona of the low back. Extirpation</td>
<td>21.3</td>
<td>26</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Anaesthesia was induced with thiopentone 5 mg kg$^{-1}$ i.v. or methohexitone 20 mg kg$^{-1}$ rectally and fentanyl 2 μg kg$^{-1}$ i.v. Tracheal intubation was performed after administration of alcuronium 0.3 mg kg$^{-1}$ i.v. The patients' lungs were ventilated mechanically with a volume controlled mechanical ventilator (Servo 900 C, Elema Schönander Inc, Stockholm, Sweden) using 70% nitrous oxide in oxygen and ventilatory frequency and tidal volume ($\approx 10$ ml kg$^{-1}$) were adjusted to maintain an end-tidal $PCO_2$ near 4.5 kPa. A Humid Vent I or a Humid Vent Mini (Gibeck Respiration Inc, Upplands Väsby, Sweden) was used for airway humidification and heat and moisture exchange.

After induction of anaesthesia the surgical area was prepared and the patients were covered with a disposable paper operation sheet. The patients lay on an operating room table covered with a foam mattress, without any external heating. Additional doses of fentanyl 1--2 μg kg$^{-1}$ i.v. and thiopentone 1--2 mg kg$^{-1}$ i.v. were given as needed during operation. Neuromuscular block was maintained with alcuronium 0.1 mg kg$^{-1}$ i.v. to maintain a one or two twitch mechanical response to train-of-four stimulation of the ulnar nerve.

At the end of surgery, neuromuscular block was antagonized with neostigmine 0.05 mg kg$^{-1}$ and glycopyrronium 0.01 mg kg$^{-1}$. During operation, both maintenance fluid therapy (Ringer's lactate with 5% glucose 4 ml kg$^{-1}$ h$^{-1}$) and volume substitution in the event of bleeding were infused through a blood warmer.

**Calculations**

An area-weighted, age-adjusted reference mean skin temperature was calculated from the tempera-
Table 11. Weighting coefficients for calculation of mean skin temperature (T\text{sk}) at various ages. Placement of the respective skin temperature sensors (T_{site}) is shown in figure 1. T\text{adef} = age-adjusted area-weighted mean skin temperature from 15 sites; T_{12site} = area-weighted mean skin temperature from 15 sites using adult weighting coefficients; T_{12} = 12-site model of Hardy and Dubois [6, 9]; T_{sk} = eight-site modification of the seven-site method of Hardy and Dubois; T_{skoop} = seven-site method of Hardy and Dubois; T_{sk} = area-weighted four-point method according to age; T_{sk} = simplified paediatric four-point method from T_{sk}; T_{sk} = four-point method of Ramanathan [11].

<table>
<thead>
<tr>
<th>Age (yr)</th>
<th>T_{sk}</th>
<th>T_{sk}</th>
<th>T_{sk}</th>
<th>T_{sk}</th>
<th>T_{sk}</th>
<th>T_{sk}</th>
<th>T_{sk}</th>
<th>T_{sk}</th>
<th>T_{sk}</th>
<th>T_{sk}</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 1</td>
<td>0.19</td>
<td>0.14</td>
<td>0.20</td>
<td>0.08</td>
<td>0.06</td>
<td>0.05</td>
<td>0.11</td>
<td>0.10</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>1-4</td>
<td>0.17</td>
<td>0.14</td>
<td>0.20</td>
<td>0.08</td>
<td>0.06</td>
<td>0.05</td>
<td>0.13</td>
<td>0.10</td>
<td>0.07</td>
<td></td>
</tr>
<tr>
<td>5-9</td>
<td>0.13</td>
<td>0.14</td>
<td>0.20</td>
<td>0.08</td>
<td>0.06</td>
<td>0.05</td>
<td>0.16</td>
<td>0.11</td>
<td>0.07</td>
<td></td>
</tr>
</tbody>
</table>

The age-adjusted weighting coefficients (c) are listed in table 11.

Change in body heat content ΔQ_{BHIC} (from the beginning to the end of operation) was calculated for each of the five patients from a generalized form of Burton’s equation [1]:

\[ ΔQ_{BHIC} = m \cdot c \cdot ΔT_b \]

where \( m \) = body mass, \( c \) = specific heat of the body (3.48 \text{kJ kg}^{-1} \text{C}^{-1}) [1] and \( T_b \) = mean body temperature. \( ΔT_b \) is given by:

\[ ΔT_b = x \cdot ΔT_c + (1-x) \cdot ΔT_{sk} \]

where \( ΔT_c \) = change in core temperature and \( ΔT_{sk} \) = change in mean skin temperature (from the first to the last sets of temperature measurements in each of the five patients) and \( x \) is a constant between 0 and 1.

The reference value of ΔQ_{BHIC} ΔQ_{BHICref} was taken as that obtained when \( T_{sk} \) was used for \( T_{sk} \). \( T_{sk} \) was used as the core temperature, \( T_c \) and \( x \) was set to 0.66 as in Burton’s original equation. Alternative values of \( ΔQ_{BHIC} \) (ΔQ_{BHICref}) were calculated using the other versions of \( T_{sk} \) instead of \( T_{sk} \) and using values of \( x \) of 0.6, 0.7, 0.8 and 0.9. The resulting values of ΔQ_{BHIC} were also expressed as difference from \( ΔQ_{BHICref} \).

Statistical analysis

The SAS program (SAS Institute Inc, NC, U.S.A.) was used in calculations. Mean skin temperatures were calculated with different formulae for the 162 sets of measurements and the means (SD) of the 162 values were determined. The differences between \( T_{sk} \) and \( T_{sk} \) were calculated and the means (SD) and the cumulative frequency distribution of the differences were determined. The agreements of the

\[ \text{Weighting coefficients for calculation of mean skin temperature (T}_{sk} \text{) at various ages. Placement of the respective skin temperature sensors (T}_{site} \text{) is shown in figure 1. T}_{adef} \text{ = age-adjusted area-weighted mean skin temperature from 15 sites; T}_{12site} \text{ = area-weighted mean skin temperature from 15 sites using adult weighting coefficients; T}_{12} \text{ = 12-site model of Hardy and Dubois [6, 9]; T}_{sk} \text{ = eight-site modification of the seven-site method of Hardy and Dubois; T}_{skoop} \text{ = seven-site method of Hardy and Dubois; T}_{sk} \text{ = area-weighted four-point method according to age; T}_{sk} \text{ = simplified paediatric four-point method from T}_{sk}; T}_{sk} \text{ = four-point method of Ramanathan [11].} \]
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### Table III. Rectal (T_{rk}) , oesophageal (T_{wc}) and 15-site reference mean skin temperature (T_{skref}) for the five patients and the differences between last and first readings (ΔT_{sk}) (mean (SD))

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>T_{rk} (°C)</th>
<th>ΔT_{rk} (°C)</th>
<th>T_{wc} (°C)</th>
<th>ΔT_{wc} (°C)</th>
<th>T_{skref} (°C)</th>
<th>ΔT_{skref} (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>36.3 (0.4)</td>
<td>-1.30</td>
<td>35.7 (0.3)</td>
<td>-0.79</td>
<td>32.8 (0.3)</td>
<td>+0.15</td>
</tr>
<tr>
<td>2</td>
<td>35.9 (0.1)</td>
<td>-0.09</td>
<td>35.9 (0.2)</td>
<td>0.10</td>
<td>33.1 (0.4)</td>
<td>+0.59</td>
</tr>
<tr>
<td>3</td>
<td>35.8 (0.2)</td>
<td>-0.54</td>
<td>35.9 (0.3)</td>
<td>-0.82</td>
<td>31.8 (0.3)</td>
<td>-0.01</td>
</tr>
<tr>
<td>4</td>
<td>36.2 (0.1)</td>
<td>-0.19</td>
<td>36.5 (0.1)</td>
<td>-0.04</td>
<td>32.0 (0.5)</td>
<td>+0.23</td>
</tr>
<tr>
<td>5</td>
<td>36.2 (0.1)</td>
<td>-0.10</td>
<td>36.0 (0.1)</td>
<td>-0.12</td>
<td>31.5 (0.2)</td>
<td>-0.67</td>
</tr>
</tbody>
</table>

### Table IV. Mean skin temperatures (T_{sk}) and skin temperatures of the forehead, abdomen and forethigh of the 162 sets of measurements. The differences calculated between each T_{sk} and the corresponding value of the 15-site reference method (T_{skref}) (mean (SD)) and the agreement frequencies between T_{sk} values and T_{skref} within 0.2, 0.5, 1.0 and 2.0 °C. T_{skref} was the arithmetic mean from 15 sites (other terms as in Table III)

<table>
<thead>
<tr>
<th>T_{sk} (°C)</th>
<th>Difference T_{sk} - T_{skref} (°C)</th>
<th>% Agreement within</th>
<th>0.2 °C</th>
<th>0.5 °C</th>
<th>1.0 °C</th>
<th>2.0 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>T_{skref}</td>
<td></td>
<td></td>
<td>95</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>T_{sk4}</td>
<td>-0.07 (0.07)</td>
<td></td>
<td>95</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>T_{sk15for}</td>
<td>-0.17 (0.06)</td>
<td></td>
<td>66</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>T_{sk15sd}</td>
<td>+0.14 (0.08)</td>
<td></td>
<td>76</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>T_{sk4}</td>
<td>+0.19 (0.34)</td>
<td></td>
<td>27</td>
<td>83</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>T_{sk7}</td>
<td>+0.39 (0.82)</td>
<td></td>
<td>3</td>
<td>17</td>
<td>72</td>
<td>100</td>
</tr>
<tr>
<td>T_{sk4}</td>
<td>-0.11 (0.57)</td>
<td></td>
<td>21</td>
<td>59</td>
<td>94</td>
<td>100</td>
</tr>
<tr>
<td>T_{sk4}</td>
<td>-0.14 (0.52)</td>
<td></td>
<td>30</td>
<td>61</td>
<td>94</td>
<td>100</td>
</tr>
<tr>
<td>T_{sk4}</td>
<td>-0.64 (0.43)</td>
<td></td>
<td>15</td>
<td>39</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>T_{sk4}</td>
<td>+1.00 (0.51)</td>
<td></td>
<td>1</td>
<td>19</td>
<td>54</td>
<td>97</td>
</tr>
<tr>
<td>T_{sk4}</td>
<td>+1.70 (1.97)</td>
<td></td>
<td>4</td>
<td>16</td>
<td>33</td>
<td>35</td>
</tr>
<tr>
<td>T_{sk4}</td>
<td>-0.33 (1.16)</td>
<td></td>
<td>18</td>
<td>30</td>
<td>66</td>
<td>88</td>
</tr>
</tbody>
</table>

Various T_{sk} within 0.2, 0.5, 1.0 and 2.0 °C of the T_{skref} were considered and a 95% agreement within 0.5 °C of the T_{skref} was taken as an acceptable limit.

RESULTS

Measurements were performed in the normothermic or slightly hypothermic range; over the 162 sets of measurements, T_{skref} ranged from 30 to 34 °C and T_{sk} from 35.2 to 36.6 °C. Mean (SD) T_{skref} T_{wc} and T_{sk} values for each of the five patients are listed in Table III together with the differences in the last and first values of the same temperatures required for calculating ΔQ_{BHCB}.

ΔQ_{BHCB} values (including three solo sites) are listed in Table IV together with the difference of each T_{sk} from the corresponding value of T_{skref}. Also shown are the percentages of the values for each T_{sk} which agree with the T_{skref} values to within four different limits.

At least 12 skin sites were required to obtain an accuracy of 0.5 °C compared with T_{skref}. The arithmetic mean of the non-weighted skin temperatures of the 15 sites agreed more closely with T_{skref} than did the mean value obtained using adult weighting coefficients in children. An area-weighted eight-site mean skin temperature agreed 100% within 1 °C with T_{skref} and the four-site model 94%.

If only one skin area (T_{f}, forehead; T_{a}, abdomen or T_{11}, forethigh) was taken to represent mean skin temperature, the agreement with T_{skref} was poor (Table IV).

The differences in alternative values of change in body heat content, ΔQ_{BHCB} from the reference value, ΔQ_{BHCBref} are shown in Figure 2 for each patient. When ΔQ_{BHCB} was calculated with different equations for mean skin temperature using 12, eight, seven or four skin sites, the difference from the reference ΔQ_{BHCBref} was greatest with the four-point method. The core temperature selected and the coefficient x in the T_{c} formula effected more changes in the differences than did mean skin temperature.

DISCUSSION

Twelve skin sites were required to obtain an estimate of mean skin temperature within 0.5 °C of the reference value during anaesthesia in children. However, mean skin temperature had the least effect in Burton's equation on the final result of change in body heat content, while core temperature selected and coefficients used in the equation of body temperature were more important. If an accuracy of 1 kJ kg⁻¹ in heat deficit is accepted, as little as four skin sites give a satisfactory estimate of mean skin temperature.

The different formulae for calculation of mean skin temperature have been divided by Nielsen and Nielsen [8] into four groups: area-weighted formulae [5-7, 9], derived regression formulae [10], physiological formulae [14, 15] and modifications [9, 14]. An ideal method might be weighting in proportion to the volume of tissue enclosed by the area which is sampled by each sensor. We chose a surface-area-weighted calculation method because the surface area changes as the child grows [12]. The weighting coefficients for children of different ages were obtained from the only available tables on the relative skin temperatures of the forehead, abdomen and forethigh.

proportions of different body regions in different ages from work published by Lund and Browden in 1944 [13]. This work is based on physiological measurements by DuBois and DuBois (1915) [16] and Boyd (1935) [12].

The use of adult weighting coefficients caused a greater difference to the reference value in the 15-site mean skin temperature model than did the arithmetic mean of the 15-site model (table IV). Therefore, it is better to use the arithmetic mean skin temperature model than the adult model in children. The four-site models with age-adjusted area-weighted coefficients were closer to the 15-site reference model than the adult model in children. The four-site model is so great in different postures.

Several factors affect local skin temperatures during surgery such as covering [17], clothing, posture, wound, lights, external heating and i.v. infusions. Stable thermal conditions are presupposed in physiological studies on heat debt. This implies that at the start and end of the experiment skin temperature should be stabilized. Pain, the level of consciousness and anaesthesia, covering, bleeding, etc, are factors which may alter skin temperature rapidly at the beginning and end of operation. This makes skin temperature a very unstable variable in Burton’s equation during operation, even if the mathematical estimate is precise.

The number of skin sites is problematic during operation as, for practical reasons, it is not always possible to put several sensors on the skin. The thermal conditions may change also, between warm and cold, during operation. After induction of anaesthesia, heat is redistributed as core temperature decreases secondary to mixing of cool peripheral blood after vasodilatation with warmer central blood [18, 19] and when the body cavities are opened the patient loses more heat to the environment. Skin temperature varies maximally between 20 and 37 °C. Measurements in this study were performed in

In this formula more emphasis is placed on the trunk, as the head area, which is proportionally larger in small children, is included in the trunk area and, respectively, less emphasis on the extremities compared with the equation of Ramanathan [11]. The eight-site model gave better results than the seven-site model of Hardy and DuBois [6], because it regarded the posterior trunk separately while in the seven-site model the abdominal skin area represents the entire trunk. During anaesthesia, the patient must lie on the operating table with one side of the trunk facing the table with the other side open to the environment. The eight-site method still omits the dorsal and volar side of the extremities, which are regarded in the 12-point model. The four-point method is very approximate as it only accounts for skin sites on the front side of the body. This explains why the difference between the 15-site model is so great in different postures.

One peripheral skin temperature can be used for circulatory monitoring during operation. In the search for a single skin temperature to represent the entire body area, we have chosen the abdomen and front of thigh areas as in earlier studies [9–11]. The forehead was selected also, because in children the head area is relatively large. None showed good agreement with the reference value. The forehead seems to be a thermally stable area, the mean temperature in that area did not show any great alterations during measurements and was 1 °C greater than the reference mean skin temperature. Most of the temperature variations occur in the extremities and abdominal areas and it is important to consider these areas separately in the calculation of mean skin temperature.
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REFERENCES