A combination of convective and conductive warming ensures pre- and post-bypass normothermia in paediatric cardiac anaesthesia

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Abstract

Background: We conducted an audit to investigate the efficacy of a proposed standard operating procedure (SOP) on convective and conductive perioperative thermal management during paediatric cardiac anaesthesia.
Methods: We retrospectively studied 26 consecutive children who underwent cardiac surgery under cardiopulmonary bypass (CPB). We applied a heating mattress and a forced-air blanket during anaesthesia induction, before CPB, during the rewarming period, and after discontinuation of CPB. Core body temperatures were recorded continuously.
Results: All children (aged 1 day to 13.5 yr, median 25 months) were divided into three groups: < 5 kg (group I, n = 9), 5–15 kg (II, n = 8), and > 15 kg (III, n = 9). Mean (± SD) core body temperatures were as follows: at the start of surgery 35.8 ± 1.0°C (I), 35.9 ± 0.6°C (II), and 36.3 ± 0.3°C (III); at the start of bypass 35.9 ± 1.1°C (I), 36.4 ± 1.1°C (II), and 36.5 ± 0.7 °C (III). Temperatures after rewarming were 36.4 ± 0.4 °C (I), 36.2 ± 0.4 °C (II), and 36.0 ± 0.4°C (III). After weaning from bypass, core body temperatures were 36.7 ± 0.9°C (I), 37.3 ± 0.7°C (II), and 37.1 ± 0.7°C (III). Normothermia on admission to ICU was maintained in all but three small infants.
Conclusions: In children undergoing cardiac surgery, a combination of convective and conductive warming can effectively ensure perioperative normothermia before and after CPB.

Introduction

During paediatric cardiac surgery, hypothermia is systematically induced for neuroprotection via cardiopulmonary bypass (CPB), with rapid re-warming before weaning from CPB. However, after discontinuation of CPB, childrens' body temperature commonly decreases (1).This phenomenon is caused by redistribution of heat from the rapidly rewarmed core to the more slowly rewarming body periphery ("afterdrop") as well as by a sustained negative heat balance (2). Because of their large body surface to body mass ratio, children are particularly prone to hypothermia (3). Contributing factors include the large surgical field in paediatric cardiac surgery and the ample amounts of fluids and blood products required for volume replacement after weaning from CPB. Resulting hypothermia is associated with an array of unfavourable effects, such as postoperative shivering with increased oxygen consumption, arrhythmias, hemodynamic instability, coagulopathy, and an increased incidence of postoperative wound infections (4-6).

Whereas many centres have introduced standard operating procedures (SOPs) for perioperative thermal

management in paediatric cardiac anaesthesia, there exist only scarce data on the prevention of perioperative hypothermia or the efficacy of such SOPs in this clinical setting. In particular, the use of convective heat systems has not yet been extensively investigated in this distinct patient population. To the best of our knowledge, there only has been one study published dedicated to this issue (7). In the present article, we report on the findings of a retrospective audit conducted to investigate the efficacy of a proposed institutional SOP at University Medical Centre Göttingen for perioperative heat management during paediatric cardiac surgery, which include the use of a combination of a forced-air body blanket for convective warming and a conductive heating mattress. The results of this audit should serve as a basis for future prospective trials to study the efficacy of different thermal management regimens in paediatric cardiac anaesthesia.

Methods

Study design and patient selection

With approval of the institutional human research committee, we retrospectively analysed the charts of 26 consecutive children aged below 15 yr who had undergone a cardiac surgical procedure at University Medical Centre Göttingen, in whom a standardised thermal management regimen had been applied, and who had been managed by one single anaesthesiologist (A. B.) and one single surgeon to minimise the effects of practice variations.

Thermal management and temperature recording

Immediately after arrival in the operating room, all children had been placed on a conductive heating mattress (Comfort-Pad Plus™, Cincinnati Sub-Zero Products Inc., Cincinnati, OH, USA) with gel-coating (Granulab International, Amersfoort, Netherlands) on the table. Then, a forced-air blanket (Care drape lower body blanket™, Mallinckrodt Medical, St. Louis, MO, USA) had been positioned on the body and a forced-air warmer (WarmTouch 5800™, Mallinckrodt Medical, St. Louis, MO, USA) connected. The forced-air device had been adjusted to 43°C and the heating mattress to 41°C. Anaesthesia had been induced and maintained with fentanyl, midazolam and pancuronium, supplemented with isoflurane. For central venous and arterial cannulation and for bladder catheterization, the children had only been uncovered to the extent necessary. Respiratory gases had been conditioned by a heat and moisture exchanger (HME). Core body temperature had been continuously measured via urinary catheter thermometer (Foley Catheter with temperature probe™, Mallinckrodt Medical, St. Louis, MO, USA). For surgical positioning of the children, the forced-air blanket had been placed over both legs, omitting one groin for potential peripheral connection of the CPB. By these means, the children had been warmed until the start of extracorporeal circulation, with a target body temperature of 36°C.

With the onset of cooling on CPB, convective and conductive warming had been discontinued. The extent of hypothermia had been chosen at the surgeon's discretion and depending on the intended surgical procedure. At the beginning of extracorporeal rewarming, conductive and forced-air warming had been resumed. Below core body temperatures of 34°C, the forced air warmer had been adjusted to 38 to 43 °C until the end of the operation to aim for normothermia. During transport to intensive care unit (ICU) all children had been covered with a customary hospital blanket.

Blood products transfused after separation from CPB had been pre-heated to 37°C (Barkey Plasmatherm™, Barkey GmbH & Co. KG, Leopoldshöhe, Germany) but cooled down again to approx. 25°C in the application syringe. No in-line transfusion or infusion warmers had been used. Room temperature was set to 21–22°C.

Data sampling and statistical analysis

We recorded the following variables: Age, body weight, body height, body surface area (BSA), duration of anaesthesia induction, pre-CPB surgery time, duration of CPB, aortic cross clamping time (= start and end of cardiac arrest), post-CPB surgery time, rewarming time on CPB, core body temperature at the beginning of surgery, core body temperature at the beginning of CPB, lowest core body temperature on CPB, core body temperature at the end of CPB, core body temperature at the end of surgery, core body temperature on admission to ICU, volume infused after weaning from CPB (packed red blood cells, fresh frozen plasma, platelets, crystalloids, colloids, blood from cell saver, and hemofiltrated blood from CPB).

Statistical analysis of temperature data was carried out with the use of one-way repeated measures analy-

sis of variance (ANOVA) with Tukey's multiple comparison test for *post hoc* testing, and the Wilcoxon signed-rank test to test for differences from a theoretical median (36.0°C; selected as the lower limit of normothermia) for robustness. We used the Kolmogorov-Smirnov test prior to parametric testing to ascertain that values followed a Gaussian distribution. Pearson's correlation was used to test for linear relationship between two Gaussian variables. Differences were considered significant at $P < 0.05$. Data are expressed as mean ± SD, n = sample size, unless mentioned otherwise. A one-tailed *post hoc* power analysis was performed following completion of data entry for the audit so as to exclude the presence of a type 2 error in the statistical exclusion of hypothermia. The data were analyzed using Microsoft Excel version 2003 (Microsoft Corporation, Redmond, WA, U.S.A.), Prism version 5, and Statmate version 2 software (GraphPad, San Diego, U.S.A.). For variables other than temperature, we limited our data analysis to descriptive statistics and refrained from significance testing.

Results

We studied a total of twenty-six children, aged between 1 day and 13.9 yr (median, 25 months), with a body weight between 2.0 and 52 kg (median, 11.9 kg) and a median body surface area (BSA) of 0.53 m^2 (range, 0.15–1.51 m^2) (Tab. 1). Preoperative diagnoses included pulmonary stenosis; complete atrioventricular septal defect; hypoplastic aortic arch; partial abnormal pulmonary venous connection; aortic stenosis; atrial septal defect; coarctation of the aorta; ventricular septal defect; transposition of the great arteries; interrupted aortic arch; subaortic stenosis; single ventricle; pulmonary atresia; mitral stenosis; patent ductus arteriosus; and combinations thereof. Table I shows the other demographic, biometric, and intraoperative data of all children. One child receiving an aorto-pulmonary shunt was operated in normothermia. All other children were cooled via CPB. Six children were operated in mild (32.0–35.9°C), twelve in moderate (25.0–31.9°C), and three in deep (15.0–24.9°C) hypothermia. In four children, hypothermic circulatory arrest was established. For better comparability, we stratified the children into three groups based on body weight: < 5 kg (group I; n = 9), 5–15 (group II; n = 8), and > 15 kg (group III; n = 9).

Mean core body temperatures at various stages of the procedures were comparable in all three groups ($P > 0.05$; Tab. 1 A–C, figures 1 A–C and 2). At the start of surgery, mean core temperatures were 35.8 ± 1.0°C (group I), 35.9 ± 0.6°C (II), and 36.3 ± 0.3°C (III) (analysis for deviation from 36.0°C: $P > 0.05$). Three out of nine patients in group I had baseline temperatures below 36.0°C; for groups II and III, these numbers were 4/8 and 2/9, respectively. There was no correlation between the duration of anaesthesia induction core and body temperature at beginning of surgery (Figure 2). Temperatures at the start of CPB were 35.9 ± 1.1°C (I), 36.4 ± 1.1°C (II), and 36.5 ± 0.7°C (III) (compared to start of surgery: $P > 0.05$; analysis for deviations from 36.0°C: $P > 0.05$). The proportion of children with temperatures below 36.0°C at this point were 3/9 (I), 2/8 (II), and 1/9 (III). The lowest intraoperative temperature, as dictated by surgical requirements and achieved via CPB, averaged 27.2 ± 5.3°C (I), 26.9 ± 5.2°C (II), and 28.3 ± 6.9°C (III) (all groups: range, 14.8–36.1°C; median, 28.8°C). Children were rewarmed on CPB to 36.4 ± 0.4°C (I), 36.2 ± 0.4°C (II), and 36.0 ± 0.4°C °C (III). At the end of surgery and after weaning from CPB, core body temperatures were 36.7 ± 0.9°C (I), 37.3 ± 0.7°C (II), and 37.1 ± 0.7°C (III) (compared to start of surgery: $P > 0.05$). Statistical testing of these data for deviations from the lower normothermic limit of 36.0°C revealed no differences for group I (actual median, 36.8°C; $P > 0.05$) and higher temperatures for groups II and III (actual medians, 37.3° and 37.0°, respectively; $P < 0.05$). There were no children in groups II or III with a core temperature below 36.0°C at the end of surgery. One child in group I, a three day-old newborn with a body weight of 4.1 kg, had mild post-CPB hypothermia (35.2°C). In this case, severe haemorrhage after discontinuation of CPB required extensive volume replacement exceeding the calculated total blood volume (380 ml).

The mean core temperature of all n = 26 children at the end of surgery was 37.1 ± 0.8°C. A *post hoc* power analysis revealed a minimum power of 80% at $\alpha = 0.05$ to detect a hypothermic deviation of 0.37°C from 36.0°C.

All but three small infants (group I) were normothermic on admission to ICU (Tab. 1 A-C). Mean core body temperatures immediately recorded after arrival were 36.5 ± (group I), 37.7 ± 0.4 (group II), and 37.7 ± 0.7 °C (group III).

Volume requirements after weaning from CPB were high in all children, particularly in group I (Table I). No thermal skin damage was documented in any child.

Table 1 A-C: Patient characteristics, time intervals, core body temperatures, and post-CPB volume replacement (weight groups I - III).

A Group I (< 5 kg) (n = 9)

Pt.	Age [m]	Body weight [kg]	BSA [m²]	Heart defect	Duration of anesthesia induction [min]	Pre-CPB time [min]	CPB time [min]	Re-warming time on CPB [min]	Post-CPB time [min]	Temp. at beg. of surgery [°C]	Temp. at beg. of CPB [°C]	Lowest temp. on CPB [°C]	Temp. at end of CPB [°C]	Temp. at end of surgery [°C]	Temp. on adm. to ICU [°C]	Volume infused after CPB [ml]	Vol. infused after CPB [ml kg^{-1} x h^{-1}]
4	5	4.3	0.26	CAVSD	45	104	190	70	40	36.4	35.5	25.2	35.9	36.8	36.8	190	66
5	0.07	3.5	0.22	AS, ASD, PDA	45	50	150	60	60	36.3	35.2	32.9	35.9	36.0	36.2	180	51
8	3.5	4.4	0.26	CAVSD	105	80	195	85	50	37.0	36.9	24.9	36.4	37.4	37.2	220	60
10	0.22	4,1	0.24	TGA, VSD, HAA	100	85	300	135	60	33.4	33.4	19.4	36.6	35.2	34.6	380	93
18	0.3	4.2	0.24	TGA, ASD	70	67	173	83	60	35.4	36.3	27.5	36.2	36.0	35.6	190	44
21	1.2	2.0	0.15	IAA, VSD	70	152	188	125	60	36.0	36.1	21.0	36.8	36.4	34.6	190	95
23	1.3	4.4	0.23	PA	50	40	80	80	110	36.1	36.1	36.1	37.0	37.6	38.2	390	48
24	4.5	4.6	0.25	VSD, PS, APW	75	60	135	65	50	36.0	37.1	29.5	37.0	37.5	37.3	210	55
25	5	4.8	0.28	CAVSD	100	42	145	65	55	35.7	36.5	28.5	36.2	37.6	37.6	190	43
Mean					73	76	173	85	61	35.8	35.9	27.2	36.4	36.7	36.5	238	62
Median	1.3	4.3	0.24														
Stdv					24	36	60	27	20	1.0	1.1	5.3	0.4	0.9	1.3	84	20

B Group II (5-15 kg) (n = 8)

Pt.	Age [m]	Body weight [kg]	BSA [m²]	Heart defect	Duration of anesthesia induction [min]	Pre-CPB time [min]	CPB time [min]	Re-warming time on CPB [min]	Post-CPB time [min]	Temp. at beg. of surgery [°C]	Temp. at beg. of CPB [°C]	Lowest temp. on CPB [°C]	Temp. at end of CPB [°C]	Temp. at end of surgery [°C]	Temp. on adm. to ICU [°C]	Volume infused after CPB [ml]	Vol. infused after CPB [ml kg^{-1} x h^{-1}]
1	31	14.0	0.59	PS	40	170	140	80	75	35.9	36.3	28.0	35.7	36.8	37.5	660	38
2	19	11.0	0.48	CAVSDl	45	42	93	45	75	34.7	34.3	20.5	36.1	36.3	37.4	670	49
6	8.5	5.6	0.30	CAVSD, CoA	100	60	245	120	125	36.6	36.8	18.1	35.8	37.2	37.7	110	9
7	42	13.3	0.59	VSD	55	67	70	50	55	36.0	36.1	29.1	36.6	38.1	38.4	210	17
11	12	10.0	0.44	SAS	70	175	150	60	120	36.3	38.2	26.0	36.0	37.4	38.2	490	25
13	34	12.7	0.57	ASD	60	55	61	35	70	35.6	36.3	33.6	35.9	36.6	37.6	130	9
14	9	8.4	0.39	SAS	50	52	105	60	65	35.7	35.9	29.9	36.9	37.6	37.2	140	15
17	35	14.8	0.60	PS, ASD, VSD	35	87	103	35	85	36.3	37.1	30.1	36.2	38.0	37.4	190	9
Mean					57	89	121	61	84	35.9	36.4	26.9	36.2	37.3	37.7	325	21
Median	25.0	11.9	0.53														
Stdv					21	53	59	28	25	0.6	1.1	5.2	0.4	0.7	0.4	242	15

C Group III (> 15 kg) (n = 9)

Pt.	Age [m]	Body weight [kg]	BSA [m²]	Heart defect	Duration of anesthesia induction [min]	Pre-CPB time [min]	CPB time [min]	Re-warming time on CPB [min]	Post-CPB time [min]	Temp. at beg. of surgery [°C]	Temp. at beg. of CPB [°C]	Lowest temp. on CPB [°C]	Temp. at end of CPB [°C]	Temp. at end of surgery [°C]	Temp. on adm. to ICU [°C]	Volume infused after CPB [ml]	Vol. infused after CPB [ml kg^{-1} x h^{-1}]
3	80	23.0	0.85	HAA, PAPVC	60	130	220	85	45	36.3	35.4	20.1	36.1	36.9	37.9	820	47
9	30	17.3	0.68	ASD	55	65	45	25	45	36.4	36.1	35.0	36.7	37.1	37.1	170	13
12	80	20.6	0.85	ASD	35	45	75	30	45	35.7	36.1	33.1	36.0	36.3	36.7	390	26
15	167	48.0	1.51	MS, CoA	45	111	274	75	105	36.8	36.0	14.8	35.5	37.0	37.4	2950	35
16	30	15.2	0.61	ASD, PS	65	100	80	35	110	36.3	37.1	30.0	35.8	37.9	38.5	800	29
19	64	17.0	0.73	ASD	40	55	44	25	75	36.2	36.0	33.6	35.5	36.2	37.6	210	10
20	84	20.3	0.85	SV	45	178	187	110	170	35.9	37.7	25.6	36.6	38.3	39.1	3970	69
22	61	20.0	0.78	SAS, AS	45	65	75	40	50	36.5	36.8	33.5	36.2	37.4	37.8	230	14
26	118	52.0	1.46	SAS	60	123	82	35	80	36.3	37.0	29.4	35.9	36.6	37.4	1120	16
Mean					50	97	120	51	81	36.3	36.5	28.3	36.0	37.1	37.7	1184	29

Pt, patient; BSA, body surface area; CPB, cardio-pulmonary bypass; Temp, core body temperature; Adm. to ICU, admission to intensive care unit; Vol, volume; PS, pulmonary stenosis; CAVSD, complete atrioventricular septal defect; HAA, hypoplastic aortic arch; PAPVC, partial abnormal pulmonary venous connection; AS, aortic stenosis; ASD, atrial septal defect; PDA, patent ductus arteriosus; CoA, coarctation of the aorta; VSD, ventricular septal defect; TGA; transposition of the great arteries; IAA, interrupted aortic arch; SAS, subaortic stenosis; SV, single ventricle; PA, pulmonary atresia; MS, mitral stenosis; TCPA, total cavo-pulmonary anastomosis; APW, aortopulmonary window; Stdv, standard deviation.

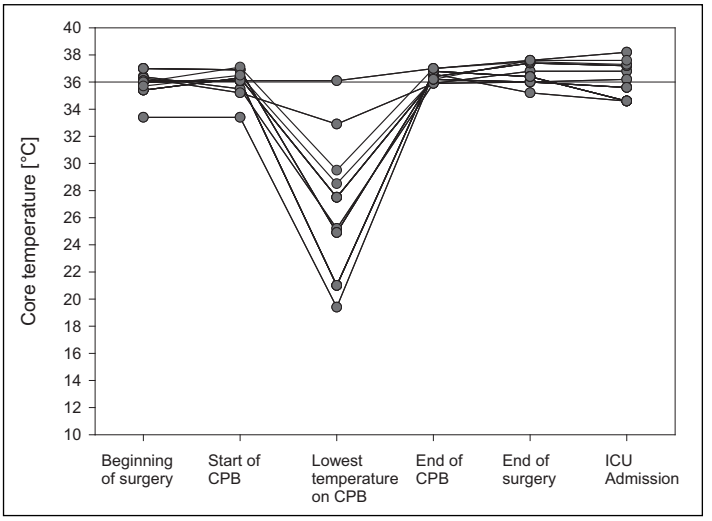

Figure 1 A. Perioperative course of core body temperatures of children < 5 kg.
CBP, cardiopulmonary bypass; ICU, intensive care unit.

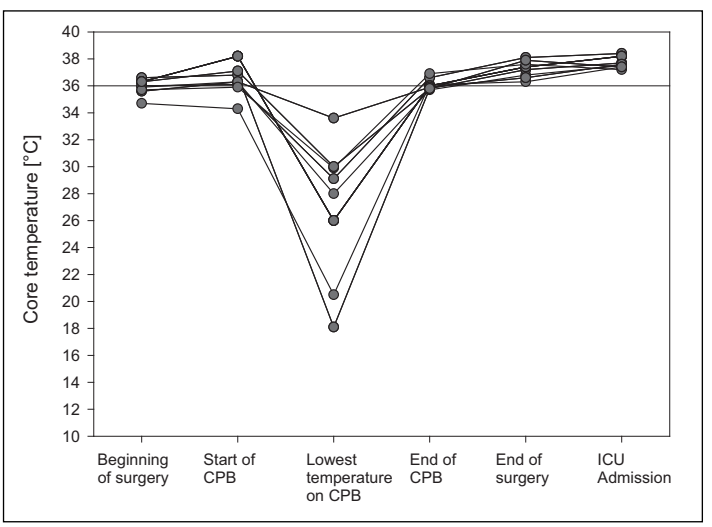

Figure 1 B. Perioperative course of core body temperatures of children 5 to 15 kg.
CBP, cardiopulmonary bypass; ICU, intensive care unit.

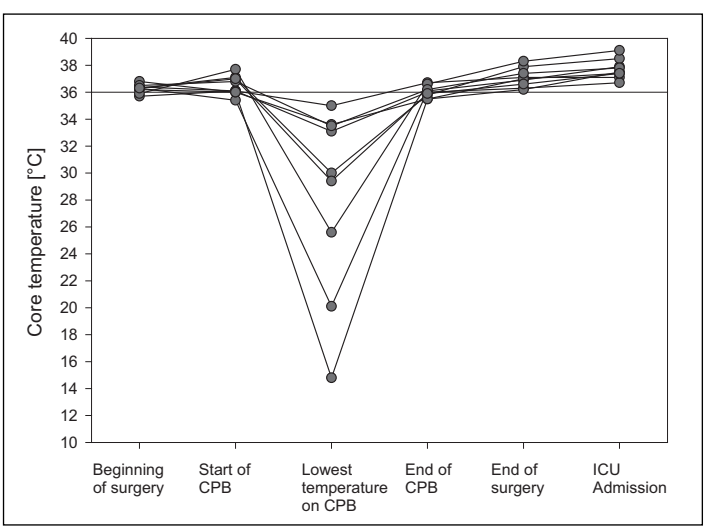

Figure 1 C. Perioperative course of core body temperatures of children > 15 kg.
CBP, cardiopulmonary bypass; ICU, intensive care unit.

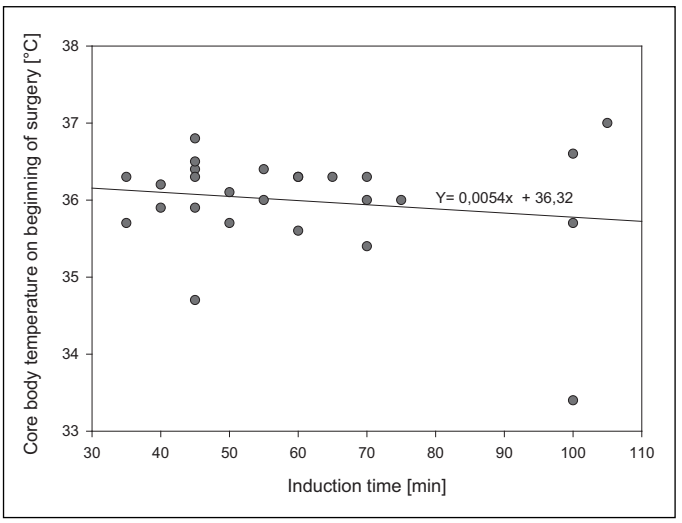

*Figure 2. Lack of correlation between anaesthesia induction time * and core body temperature at the beginning of surgery (all groups; n = 26 children; Pearson correlation coefficient, r = -0.161; r^2 = 0.026; P = 0.43).*
**Anaesthesia induction time, i.e. operating room entry to intubation, including insertion of indwelling catheters and set-up of invasive hemodynamic monitoring.*

Discussion

In this audit of a proposed institutional SOP for thermal management during paediatric cardiac anaesthesia, we found that pre-CPB normothermia was maintained in the majority of children, with nine children developing mild hypothermia at this stage (Tab. 1 A-C, Fig. 1 A-C and 2). There was no correlation between core body temperature at the beginning of surgery and the duration of anaesthesia induction, a finding we attribute to the almost complete covering with a forced-air blanket during central venous cannulation. Furthermore, by following our thermal management protocol, we were able to maintain normothermia on arrival on ICU in all but three small infants (< 5 kg) who developed mild hypothermia (34.6, 35.6, and 34.6 °C). This finding emphasizes the importance of attentive measures for effective heat preservation during transport, in particular for neonates and young infants.

Postoperative hypothermia after paediatric cardiac surgery is common. One previous study showed that on admission to ICU, most children had a core body temperature between 34 and 35°C (8). Hypothermia places further stress on the already compromised cardiovascular system by triggering tachycardia and vasoconstriction. In addition, shivering (and also non-shivering heat production in infants) produces severe metabolic stress (8,9). Hypothermia also leads to coagulopathy with resultant increased postoperative blood loss, and increases the incidence of wound infection (10).

As is the case for other surgical procedures, avoidance of hypothermia before the start of CPB is useful for maintenance of homoeostasis. A study on newborns undergoing cardiac surgery showed that core body temperature fell during induction of anaesthesia and surgery prior to the start of CPB to an average of 31 ± 0.6°C if no specific thermal protection measures were taken (11). Hypothermia was associated with a decrease in heart rate and a severe increase in base excess to –6.7 ± 3.3 mmol/l and serum lactate levels to 3.5 ± 1.6 mmol/l, both indicative of impaired systemic perfusion.

Constant core body temperature after the beginning of surgery and before the start of CPB is indicative of adequate heat preservation, despite median thoracotomy and long preparation times of up to 178 min in children undergoing repeated surgery.

Before weaning of CPB, normothermia is routinely aimed for; rewarming is mainly achieved via extracorporeal circulation, a technique very effective in terms of maximum heat transfer. Its efficacy depends on two factors: Blood flow via CPB and temperature gradient between venous and arterial patient blood. Initially, CBP generates high rewarming rates of up to 10°C h^{-1}; however, subsequent temperature decrease significantly decelerates rewarming efficacy (12). At this stage, application of vasodilators and increased blood flow may accelerate rewarming of the body periphery (2). Nonetheless, further rise of arterial blood temperature (return from CPB) leads to only minor rewarming of the body periphery.

Hence, an SOP that includes a combination of external warming techniques (e.g. forced air-blankets) with invasive rewarming via extracorporeal circulation may hold some advantages: First, externally ap-

plied heat does not directly warm the body core and does not contribute to cerebral hyperthermia. Second, warming of the body periphery during rewarming on extracorporeal circulation reduces heat loss and afterdrop after weaning from CPB (2).

Although post-CPB afterdrop may be less pronounced in children because of their relatively small peripheral mass, it does occur (1). On the other hand, their large body surface makes forced-air warming particularly effective in children as body surface plays a key role in heat transfer with the environment (13). During the period encompassed by our study, forced-air under-body blankets had not been available in our institution. Whereas these may provide better handling and easier patient access, their efficacy for thermal management in paediatric cardiac anaesthesia has not yet been investigated.

The use of circulating water mattresses is common practice in cardiac anaesthesia and also was incorporated in the present perioperative heat management regimen. However, our previous findings in a manikin study indicate that the contribution of conductive heating systems to total perioperative heat exchange is small (14).

Another potential source of heat loss is the administration of non-warmed infusions and transfusions, particularly in light of the fact that administered volumes in paediatric cardiac anaesthesia are routinely considerable (15). Although this may advocate the routine use of an in-line infusion warming system, infusion-related heat losses could be compensated by convective warming in almost all of our children in the present study. Pre-warming of infusions to 37°C may decrease heat loss if high infusion rates are required, but this approach is much less effective at low rates (16). Whereas one child in our study that required massive post-CPB volume replacement may have stayed normothermic had an effective infusion warming system been used, our data do not support their general use in paediatric cardiac anaesthesia since conductive and forced-air warming techniques alone appear to provide adequate heat management.

Lastly, respiratory heat loss contributes during paediatric cardiac anaesthesia and can be easily and effectively controlled with the use of a heat and moisture exchanger (17,18).

Limitations

In accordance with our clinical routine, we measured urinary bladder temperature to obtain core body values. This technique has come into discussion as profound and rapid changes of core body temperature may not be accurately reflected by bladder measurements. However, urinary bladder temperature monitoring is widely used for operations on CPB and its sufficient accuracy has been demonstrated by several authors (19,20).

Speculations

The present data from this retrospective audit support the hypothesis that attentive perioperative thermal management with a standardised regimen that combines conductive warming and convective warming is effective in maintaining normothermia before and after paediatric cardiac surgical procedures. Our findings further indicate that this technique is feasible and effective for pre- and post-CPB heat preservation as well as for controlled and sustainable re-warming on extracorporeal circulation. We now aim to formally implement the proposed SOP on perioperative thermal management within our centre. Finally, the present results should serve as a basis for a comparative prospective trial to further study the efficacy of different perioperative thermal regimens in paediatric cardiac anaesthesia.

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