Equipment

Liquid crystal skin thermometry: an accurate reflection of core temperature?

Sorin J. Brull MD, Anthony J. Cunningham MD,
Neil R. Connelly MD, Theresa Z. O'Connor MPH,
David G. Silverman MD

Oesophageal, rectal, bladder, tympanic and pulmonary artery sites are used intraoperatively to measure body temperature. However, the temperatures measured at each site have different physiological and practical importance. The present two-part study sought to compare liquid crystal (CR) skin temperature with other temperature monitors which are used routinely during surgery. The first part compared CR with oesophageal (OS) temperature during general inhalational anaesthesia. The second part compared CR with OS, pulmonary artery (PA), and bladder (BL) temperatures during the periods of rapid temperature change associated with cardiopulmonary bypass (CPB). During the first part, the mean difference between OS and CR was $-0.14 \pm 0.85^{\circ}\text{C}$; this difference remained consistent over time ($P < 0.05$ by repeated measures analysis of variance). During the second part, the difference in temperature readings between CR and each of the other monitors remained consistent except for CR vs PA and CR vs OS during the cooling period of CPB, when the iced cardioplegia slush directly affected the PA and OS temperatures. This study suggests that CR, an inexpensive and noninvasive means of temperature monitoring, reflects trends in temperature changes in the clinical setting.

Key words

MEASUREMENT TECHNIQUES: liquid crystal thermometry;
SURGERY: cardiopulmonary bypass;
TEMPERATURE: monitoring.

From the Department of Anesthesiology, Yale University School of Medicine, Yale-New Haven Hospital, New Haven, CT 06510.

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Address correspondence to: Dr. Sorin J. Brull, Department of Anesthesiology, Yale University School of Medicine, 333 Cedar Street, New Haven, CT 06510, (203) 785-2802.

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Au cours d'une intervention chirurgicale, on mesure la température dans l'oesophage, le rectum, la vessie, l'artère pulmonaire ou sur le tympan. Cependant, la mesure de la température à un de ces sites n'a pas nécessairement la même importance physiologique et pratique. L'étude présentée réalisée en deux parties vise à comparer la température cutanée mesurée aux cristaux liquides (CR) avec autres moniteurs utilisés couramment pendant la chirurgie. Dans une première phase, on compare CR avec la température oesophagienne (OE) pendant l'anesthésie inhalatoire. La deuxième compare la température CR avec OE, et celles l'artère pulmonaire (AP) et de la vessie (V) pendant les périodes de changements rapides associées à la circulation extracorporelle (CEC). Pendant la première partie de l'étude, la différence moyenne entre OE et CR est de $-0,14 \pm 0,85^{\circ}\text{C}$; cette différence demeure constante dans le temps ($P < 0,05$ sur des mesures répétées d'analyse de variance). Pendant la deuxième temps, la différence de lecture entre CR et chacun des autres moniteurs concorde. Cette concordance cesse entre CR vs AP et CR vs OE, pendant la CEC, au moment du refroidissement direct par mélange cardioplégique glacé. Cette étude suggère que CR est un moniteur peu coûteux et non invasif qui reflète bien la tendance des changements de température dans le contexte clinique étudié.

The application of various temperature monitoring devices may be limited during certain surgical procedures. Oesophageal probe placement is impractical in awake patients whose tracheas are not intubated. Tympanic probe placement has the potential for ear drum perforation.¹ Pulmonary artery thermistor readings are not reliable during cardiopulmonary bypass when there is no flow through the heart and lungs, and may be directly affected by the iced cardioplegia slush used during cooling. Monitoring of bladder temperatures often is impractical and is limited by the need for continuous urinary output and by the possibility that patient positioning may place the temperature thermistor outside the urinary stream. Similar limitations may occur during rectal temperature mon-

itoring, as the thermistor may become impacted in faecal material. Axillary and peripheral skin surface temperatures, including forehead, finger, toe, and axilla, may be influenced by intraoperative changes in cardiac output and by regional vasoconstriction.²

In light of the limitations and costs that may be associated with other techniques, liquid crystal (CR) skin temperature monitoring may offer a simple, inexpensive, viable alternative in many settings. The present study assessed the ability of liquid crystal thermometry to monitor trends in temperature and to identify extreme changes in temperature in two operative settings. In Part A, the relationship between liquid crystal skin temperature and oesophageal (OS) temperature was investigated in patients undergoing general endotracheal inhalation anaesthesia for a variety of surgical procedures. It was designed to expand upon a previous study³ which concluded that liquid crystal thermometry of the forehead is not sufficiently accurate to be used as an indicator of core temperature during surgery. The present study differed with respect to the nature of the commercially available CR strip – which now has been adjusted by the manufacturer to “correct” for the typical difference between skin and core temperature – and by documenting bias at multiple time-points and reporting trends over time. In Part B, we expanded upon a previous study that had compared CR with OS, axillary, and rectal measurements during rewarming after cardiopulmonary bypass.⁴ We monitored changes during cooling, as well as rewarming, in an effort to determine the ability of CR to detect hypothermia reliably. In addition, we compared CR with two other measures of core temperature: pulmonary artery (PA) catheters, which provide the most rapid response to changes in core temperature; and to urinary bladder (BL) catheters, in an effort to determine if the latter continue to be required as a component of our intraoperative monitoring at a site that is remote from the cooled slush that is placed in the chest. The findings were used as a basis for recommendations concerning the suitability of CR for precise temperature monitoring, for detecting trends, and for identifying extremes of temperature.

Methods

Part A

Following institutional Human Investigational Committee approval, 127 patients undergoing general endotracheal inhalation anaesthesia for a variety of surgical procedures were evaluated. The anaesthetic technique was at the discretion of the primary anaesthesia care provider, and included a volatile inhalational agent (isoflurane) as the main anaesthetic in all patients. In all cases, ventilation was controlled and end-tidal carbon dioxide (CO₂)

tension was maintained between 30–40 mmHg, as documented on a continuous infra-red CO₂ monitor. Anaesthesia was delivered via a semi-closed circle system, at total fresh gas flows of 1–3 L · min⁻¹. In-line inspired gas heaters and humidifiers, as well as head wrapping and reflective covers, were not used during the study period. Intravenous fluids were infused at room temperature, while blood transfusions, if any, were administered after warming to room temperature. Following intubation of the trachea, an OS probe (Electromedics Inc, Englewood, CO) which had a precision of 0.1°C was placed in the oesophagus and was positioned to optimize monitoring of breath and heart sounds. A CR strip (Sharn Inc., Tampa, FL), which was calibrated in 1°C increments and had a range of 29–41°C, was then placed on the patient's mid-forehead. After an initial five-minute period of temperature stabilization, both the OS and CR temperatures were recorded at ten-minute intervals for a total of 90 min (i.e., from five minutes to 95 min following induction). The bias and limits of agreement between the OS and CR readings over the 90-min time period were assessed in the manner suggested by Bland and Altman.⁵ Repeated measures analysis of variance (ANOVA) was used to test for differences between the monitors and whether the difference changed over time.

In addition to the aforementioned analysis, the data sets in which one of the temperature monitors recorded less than 33.0°C or greater than 38.0°C were viewed individually. For each of these extremes, the median difference between monitors and the range of differences were recorded.

Part B

With institutional Human Investigational Committee approval, temperature changes were monitored in 17 patients during cardiopulmonary bypass (CPB) under general anaesthesia with *iv* fentanyl (50–75 µg · kg⁻¹) and isoflurane (0.25–0.5% end-tidal concentration) in oxygen. As per clinical routine, thermocouples were placed in the oesophagus (OS), pulmonary artery (PA; Baxter Healthcare Corp, Edwards Critical Care Division, Irvine, CA), and bladder (BL; Foley urinary catheter; American Pharmaseal Co., Valencia, CA). In addition, a CR strip was placed on the patient's mid-forehead. Once cardiopulmonary bypass was initiated and active cooling was begun, each of the four temperatures was recorded at one-minute intervals for a period of ten minutes. All OS, PA, and BL temperatures were displayed to the nearest 0.1°C; the CR strips were calibrated in 1.0°C increments and were estimated by the observers to the nearest 0.1°C. Data also were recorded during the rewarming period as described above, after CR increased to a temperature of greater than or equal to 29°C (monitor's lower limit).

FIGURE 1 Bias between liquid crystal (CR) and oesophageal (OS) temperatures (and 95% limits of agreement) as a function of their average. $n = 1,238$ temperature readings from 127 patients undergoing general endotracheal anaesthesia.

FIGURE 2 Mean oesophageal (OS) and liquid crystal (CR) temperature at each ten-minute interval in 127 patients undergoing general endotracheal anaesthesia.

The agreement between CR and each of the other monitors was assessed in the manner suggested by Bland and Altman.⁵ Repeated measures ANOVA was performed to determine whether temperature readings trended similarly over time for CR versus each of the other three temperature monitors. Data for both parts of the study are presented as mean $\pm$ SD; statistical significance was defined at the $P < 0.05$ level.

Results

Part A

The mean bias between OS and CR readings over all

TABLE I Intraoperative temperature readings

Time (min)	Oesophageal (°C)	Liquid crystal (°C)	Temperature difference (°C)
5	35.83 $\pm$ 0.69	35.96 $\pm$ 0.93	-0.13
15	35.84 $\pm$ 0.66	36.00 $\pm$ 0.91	-0.16
25	35.83 $\pm$ 0.61	36.00 $\pm$ 0.93	-0.17
35	35.85 $\pm$ 0.62	35.97 $\pm$ 0.96	-0.12
45	35.82 $\pm$ 0.62	35.99 $\pm$ 0.96	-0.17
55	35.83 $\pm$ 0.65	35.94 $\pm$ 1.0	-0.11
65	35.81 $\pm$ 0.67	35.96 $\pm$ 1.07	-0.15
75	35.82 $\pm$ 0.67	35.97 $\pm$ 1.04	-0.15
85	35.82 $\pm$ 0.67	35.97 $\pm$ 1.07	-0.14
95	35.83 $\pm$ 0.69	35.93 $\pm$ 1.13	-0.10

time points was $-0.14 \pm 0.85^\circ\text{C}$ (Figure 1). The mean inter-device difference at individual time points ranged from -0.10°C to -0.17°C (Table I). This difference was statistically significant ($P = 0.0001$) and remained consistent over time (Figure 2).

Of the 1,238 total number of temperature readings, there were 40 instances in which only CR was greater than 38.0°C ; in these instances, the median CR temperature was 38.2°C (range of 38.1 to 38.9°C). The corresponding OS temperatures had a median of 37.1°C (range of 36.4 – 37.8°C). The mean OS–CR bias for these 40 data points was $-1.18 \pm 0.38^\circ\text{C}$. There were no cases in which only OS was greater than 38.0°C . There were six instances in which CR was the only temperature indicator with readings below 33.0°C , and their median value was 32.2°C (range of 31.3 – 32.8°C). The corresponding OS values had a median of 34.2°C (range of 34.2 – 34.4°C). The mean OS–CR bias for these six data points was $2.17 \pm 0.43^\circ\text{C}$. There were no instances in which only OS was below 33.0°C .

Part B

As detailed in Tables II and III and illustrated in Figure 3, each monitor recorded a change over the ten-minute period of cooling and over the ten-minute period of re-warming ($P < 0.05$). These temperature changes were greatest for PA and least for CR and BL.

The mean bias ($\pm$ SD) between CR and OS during cooling was $2.09 \pm 1.9^\circ\text{C}$ (Figure 4A). The difference between the CR and OS monitors depended on time ($P < 0.05$); there were smaller temperature differences between monitors at the earlier than at the later time points. The mean bias between CR and OS during warming was $-1.49 \pm 1.7^\circ\text{C}$ (Figure 4B). There was a difference between CR and OS ($P = 0.001$), and the difference remained constant over time.

The mean bias ($\pm$ SD) between CR and PA during cooling was $4.46 \pm 3.7^\circ\text{C}$ (Figure 5A). The difference

TABLE II Temperature readings for the four monitors during cooling

Time point	Monitor			
	Liquid crystal (°C)	Oesophageal (°C)	Bladder (°C)	Pulmonary artery (°C)
	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD
1	34.55 $\pm$ 1.17	33.82 $\pm$ 1.60	34.93 $\pm$ 1.39	33.83 $\pm$ 2.07
2	34.29 $\pm$ 1.33	33.08 $\pm$ 1.60	34.68 $\pm$ 1.71	32.59 $\pm$ 2.25
3	34.04 $\pm$ 1.27	32.36 $\pm$ 1.56	34.43 $\pm$ 1.71	31.19 $\pm$ 2.21
4	33.55 $\pm$ 1.17	31.46 $\pm$ 1.66	33.81 $\pm$ 1.83	29.66 $\pm$ 2.79
5	33.06 $\pm$ 1.03	30.80 $\pm$ 1.73	33.12 $\pm$ 1.97	28.19 $\pm$ 3.48
6	32.48 $\pm$ 0.94	30.12 $\pm$ 1.70	32.17 $\pm$ 2.10	27.05 $\pm$ 3.65
7	31.80 $\pm$ 1.08	29.46 $\pm$ 1.70	31.46 $\pm$ 2.32	26.01 $\pm$ 3.83
8	31.41 $\pm$ 1.21	28.87 $\pm$ 1.71	30.83 $\pm$ 2.59	24.80 $\pm$ 3.58
9	30.99 $\pm$ 1.14	28.10 $\pm$ 1.82	30.28 $\pm$ 2.64	24.09 $\pm$ 3.79
10	30.65 $\pm$ 0.96	27.73 $\pm$ 1.84	30.23 $\pm$ 2.44	24.21 $\pm$ 3.46

FIGURE 3 Mean temperature recorded by each monitor during cooling (A) and warming (B) periods of cardiopulmonary bypass.

between the CR and PA monitors depended on time ($P = 0.0001$), with smaller temperature differences between monitors evident at earlier time points than at later time points. During warming, the bias between CR and PA was $-0.92 \pm 2.7^\circ\text{C}$ (Figure 5B). There was a difference

FIGURE 4 Bias between liquid crystal (CR) and oesophageal (OS) temperatures at one-minute intervals during cooling (A) and warming (B) in 17 patients undergoing cardiopulmonary bypass. Lines represent mean bias and 95% limits of agreement.

TABLE III Temperature readings for the four monitors during warming

Time point	Monitor			
	Liquid crystal (°C)	Oesophageal (°C)	Bladder (°C)	Pulmonary artery (°C)
	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD	Mean $\pm$ SD
1	30.18 $\pm$ 1.74	31.00 $\pm$ 2.56	30.81 $\pm$ 2.17	30.02 $\pm$ 4.95
2	30.57 $\pm$ 1.81	31.43 $\pm$ 2.66	31.11 $\pm$ 2.15	30.53 $\pm$ 4.84
3	30.99 $\pm$ 1.77	32.19 $\pm$ 2.18	31.54 $\pm$ 2.16	31.51 $\pm$ 3.44
4	31.44 $\pm$ 1.87	32.90 $\pm$ 2.07	31.89 $\pm$ 2.25	31.78 $\pm$ 4.13
5	31.99 $\pm$ 1.90	33.80 $\pm$ 1.84	32.33 $\pm$ 2.29	33.12 $\pm$ 2.76
6	32.49 $\pm$ 1.80	34.41 $\pm$ 1.80	32.62 $\pm$ 2.34	33.88 $\pm$ 2.63
7	33.04 $\pm$ 1.66	34.92 $\pm$ 1.70	33.00 $\pm$ 2.28	34.41 $\pm$ 2.39
8	33.55 $\pm$ 1.59	35.35 $\pm$ 1.52	33.35 $\pm$ 2.29	34.91 $\pm$ 2.20
9	34.10 $\pm$ 1.54	35.69 $\pm$ 1.57	33.74 $\pm$ 2.24	35.44 $\pm$ 2.02
10	34.43 $\pm$ 1.52	36.01 $\pm$ 1.42	34.00 $\pm$ 2.28	35.89 $\pm$ 1.72

FIGURE 5 Bias between liquid crystal (CR) and pulmonary artery (PA) temperatures at one-minute intervals during cooling (A) and warming (B) in 17 patients undergoing cardiopulmonary bypass. Lines represent mean bias and 95% limits of agreement.

between the CR and PA monitor readings ($P = 0.0001$), and the difference remained constant over time.

The mean bias ($\pm$ SD) between CR and BL during cooling was $0.09 \pm 1.9^\circ\text{C}$ (Figure 6A). The mean bias during warming was $-0.16 \pm 2.1^\circ\text{C}$ (Figure 6B). There were no differences between the CR and BL monitor readings during either cooling or warming periods ($P = \text{NS}$).

Discussion

Moderate hypothermia ($34\text{--}35^\circ\text{C}$) is common during anaesthesia and surgery. Following induction of anaesthesia, core temperature decreases by $0.5\text{--}1.5^\circ\text{C}$ due to vasodilation-induced mixing of cold peripheral blood with warm central blood. Core body temperature may decline further with time to a steady-state of 34.5°C to 35°C , as heat is lost to the environment.⁶ Inhalational anaesthetic agents depress the thermoregulatory threshold from a level of approximately 37°C in the normal state, to 34.5°C .⁷ The only thermoregulatory responses present in an anaesthetized, paralyzed, hypothermic patient are peripheral vasoconstriction and non-shivering thermogenesis. Hypothermia is also common in the postoperative period. It may reduce the metabolism and excretion of drugs, and may also lead to postoperative shivering with associated increases in oxygen consumption and hypoxaemia.⁸

Our data indicate that a wide variability exists between individual intraoperative temperature measurements obtained by the four monitoring devices. In Part A of this study, this variability was clearly evident for the comparisons between OS and CR temperature determinations. However, temperature trends, rather than actual temperature values, are probably more important during surgery. The two monitoring techniques (OS and CR) trended similarly, as evidenced by the consistency of the OS-CR differences over time. These data suggest that

FIGURE 6 Bias between liquid crystal (CR) and urinary bladder (BL) temperatures at one-minute intervals during cooling (A) and warming (B) in 17 patients undergoing cardiopulmonary bypass. Lines represent mean bias and 95% limits of agreement.

in surgical procedures where oesophageal temperature monitoring is not practical (i.e., neck, pharyngeal, or oesophageal surgery), liquid crystal skin temperature monitoring may provide an economic, noninvasive and reliable alternative.

In Part B of the study, during the cooling phase of cardiopulmonary bypass, CR and BL temperatures were similar. The failure of CR to trend with OS and PA temperatures during the cooling phase of cardiopulmonary bypass is due primarily to iced cardioplegia that was poured into the chest cavity at the start of the cooling period. Alternatively, during warming, CR trended with both the OS and PA temperatures.

The model of temperature changes induced by cardiopulmonary bypass has been used previously to study CR monitors. In one study,⁹ it was concluded that, although CR performed well as a trend monitor when invasive temperature monitoring was not necessary, patients undergoing major surgical procedures would be monitored best by a method which reflected core temperature more reliably. In another study evaluating patients undergoing extracorporeal circulation, it was concluded that CR may be a useful temperature trend monitor when invasive temperature monitoring is unavailable.⁴ It is important to note that the present study did not seek to define the best temperature monitor in a clinical setting such as CPB. Nevertheless, CR appears to be a useful monitor during CPB. It yielded results which were comparable with BL, and appeared to be free of some of the limitations which can affect the other temperature monitors. Based on the present study alone, we do not recommend that CR replace the other invasive monitors during CPB; however, one may argue that CR should be used as a replacement for BL due to the cost difference between these two devices and the reliance of BL on proper positioning and continued urinary output.

The classical manifestations of intraoperative malignant hyperthermia (MH) include tachycardia and tachypnoea resulting from sympathetic nervous system stimulation secondary to underlying hypermetabolism and hypercarbia. Shortly thereafter, hypertension, ventricular dysrhythmias, muscle rigidity and arterial oxygen desaturation may be noted. An increase in body temperature at a rate of 1–2°C every five minutes is commonly observed.¹⁰ The reliability and response time of liquid crystal skin temperature monitors in such a clinical situation are uncertain. High levels of catecholamines present during an MH episode produce peripheral vasoconstriction which may result in CR measurements which are not useful.¹¹ Alternatively, it also has been shown that heat loss due to radiation increases during the first 20 min of such a crisis.¹² Thus, one may see an increase in skin temperature early during an MH episode. The utility and reliability of CR monitors in such a clinical setting remain to be investigated. Moreover, it is important to note that an MH episode may produce temperatures greater than those evaluated in the present study. Alternatively, it has been reported that a linear correlation existed between liquid crystal monitors and oesophageal thermistors during whole body hyperthermia as a part of cancer treatment.¹³ Whether these data can be extrapolated to hypermetabolic states, such as MH, is unknown.

In summary, during intraoperative periods of both routine and rapid temperature changes, liquid crystal skin temperature monitor trends similarly to oesophageal, bladder, and pulmonary artery temperature monitors.

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