Anesthesiology
77:31–37, 1992

Errors in Thermodilution Cardiac Output Measurements Caused by Rapid Pulmonary Artery Temperature Decreases after Cardiopulmonary Bypass

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When systemic cooling and rewarming are performed during cardiopulmonary bypass (CPB), the pulmonary artery temperature typically decreases after CPB. This decrease may be rapid enough to cause substantial underestimation of cardiac output (CO) measured by thermodilution, due to changing baseline temperature during the thermodilution measurement. In 16 patients undergoing CPB for coronary artery grafts, digital recording of pulmonary artery temperature was done during room-temperature thermodilution CO (TDCO) injections. TDCO were computed with and without correction for baseline temperature decrease. Prior to CPB, the temperature change was −0.013° C/min, producing no significant effect on CO measurements; the coefficient of variation of CO measurements was 5.1%. One minute after CPB the temperature change was −0.144° C/min, producing a CO measurement error of −0.57 ± 0.52 l/min (SD), or about 11% of the average CO; the range of the error was 0.05 to −2.0 l/min. Ten minutes after CPB the temperature change was −0.063° C/min, and CO error was −0.31 ± 0.36 (0.15 to −1.20) l/min. At 30 min the temperature change was −0.012° C/min (not significant), and CO error was −0.13 ± 0.14 l/min. Duration of CPB was 104 ± 30 min, with rewarming for 44 ± 13 min; the average minimum bladder temperature was 25.1 ± 2.3° C during cooling and 36.7 ± 0.7° C at the end of CPB. Under these conditions TDCO measurements within the first 10 min after CPB often underestimate the true CO. (Key words: Measurement techniques, cardiac output: thermodilution. Monitoring: cardiac output. Surgery, cardiac: cardiopulmonary bypass. Temperature.)

CALCULATIONS OF THERMODILUTION cardiac outputs (TDCO) using cardiac output (CO) computers can be accurate only if the cold injectate is the sole cause of short-term temperature change in the pulmonary artery (PA). PA temperature changes from causes other than the thermodilution injectate are a source of error,[1] and manual or computer-assisted methods for TDCO calculation have included corrections for PA temperature drift.[1–3] Algorithms for automated CO computers[4] make no adjustment for changes in baseline PA temperature occurring during the CO measurement. Error in TDCO measurement as a result of changing PA temperature has been observed in association with intravenous fluid infusions[5] and during surface-induced hypothermia and rewarming.[3]

Error in CO measurement resulting from rapid PA temperature decrease after cardiopulmonary bypass (CPB) has been noted,[6] but the extent of systematic error in post-CPB thermodilution CO measurements has not been evaluated. Rapid temperature decreases routinely occur upon discontinuation of CPB after rewarming from systemic hypothermia.[7–10] Because of the post-CPB temperature decrease, we would expect that CO measured just after CBP is frequently underestimated.

We studied the temperature changes and the resulting errors in TDCO measurements in patients undergoing coronary artery bypass graft surgery. PA temperature curves were recorded using digital electronic techniques, and the TDCO errors were evaluated by calculation of CO values with and without correction for baseline temperature changes.

Materials and Methods

Subjects were 19 patients of both genders who were scheduled for coronary artery bypass surgery. Institutional approval was obtained. Patients were premedicated with morphine sulfate 0.1 mg/kg and scopolamine hydrobromide 0.2–0.4 mg. Ketamine 1.5 mg/kg, fentanyl 15 to 30 μg/kg, and a nondepolarizing muscle relaxant were administered before tracheal intubation; anesthesia was maintained using ketamine 1.5 $mg \cdot kg^{-1} \cdot h^{-1}$, fentanyl in increments (60–80 μg/kg total including induction), enflurane 0–1%, and additional muscle relaxant. Mechanical ventilation with a minute volume of 80–90 ml/kg was used initially and adjusted to approximately normocapnia; rate was 10 breaths/min, but was increased to 20 breaths/min at the same minute volume before and during recorded CO determinations to reduce ventilation-related PA temperature fluctuations.[11] ECG, a percutaneous brachial artery cannula, and a PA thermodilution catheter with a central venous pressure port (Spectramed® model SP5507H) were used for monitoring each patient. CO measurements were obtained using 10-ml room temperature manual injections; injectate temperature was measured using an in-line thermistor (Baxter® 650226003). Oropharynx temperatures were measured using a flexible thermistor probe (Yellow Springs Instru-

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Received from the Department of Cardiothoracic Anesthesia and the Department of Cardiac and Thoracic Surgery, Cleveland Clinic, Cleveland Ohio. Accepted for publication March 13, 1992.

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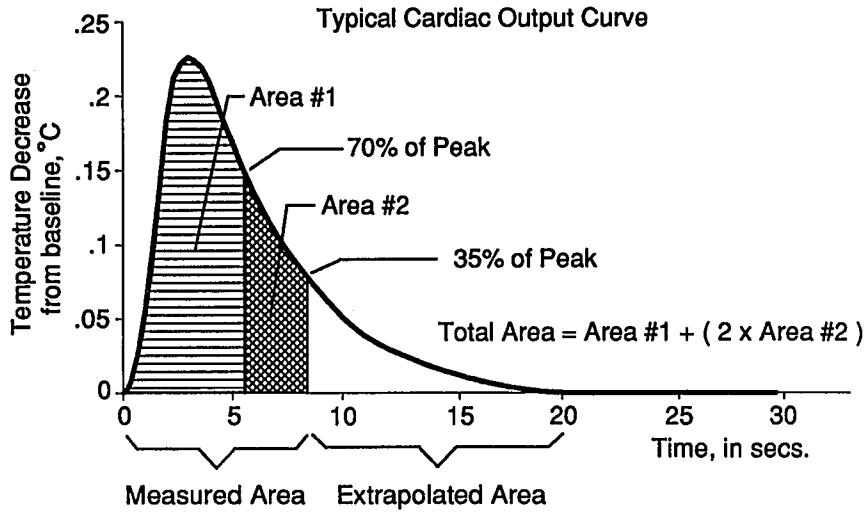
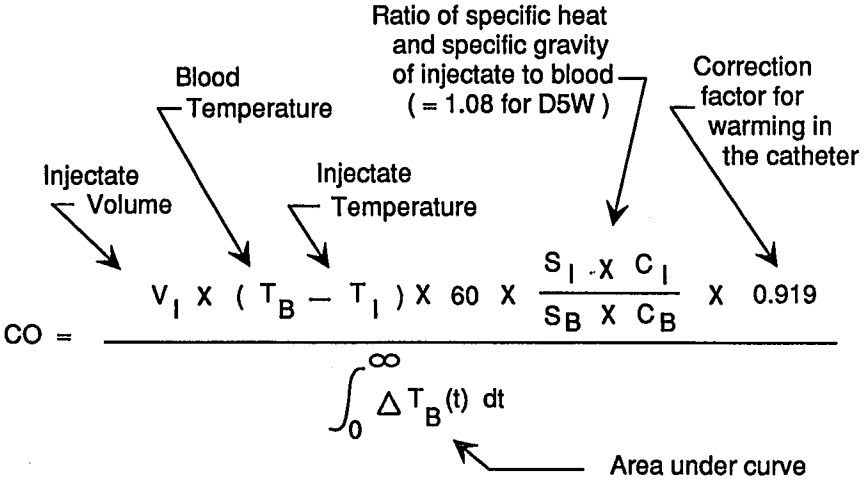


FIG. 1. Calculation of cardiac outputs. The total area under the cardiac output curve is calculated as the sum of a measured area and an extrapolated area. The measured area is the area from the start of the curve to 35% of the peak (negative) temperature change. The rest of the area is extrapolated; the extrapolated area is taken to be equal to the area between 35% and 70% of the peak temperature change. Constant terms in the Stewart-Hamilton equation are shown.



ments 700 series), and bladder temperatures were measured using a thermistor incorporated in a urinary catheter (Foley-Electromedics® 2745). Input blood temperatures were measured using a thermistor (Terumo® CX*TL) in the tubing connecting the output of the pump-oxygenator to the patient.

Analog data for injectate and PA temperatures were acquired using internal modifications to a Marquette® 7000 series CO module. Similar modifications to a Marquette® temperature module (pn 9399-04) were made to obtain pharyngeal and bladder temperatures. The analog outputs were converted to 12-bit digital temperature measurements using a Metrabyte® Dash-16 analog-to-digital converter. The system was tested using a water bath and a precision thermometer (Tektronix® 500 series P6601) and was accurate within 0.1° C for PA temperature.

Data acquisition, storage, and display were done using a microcomputer and custom software. Temperatures were sampled every 20 s throughout the case. During CO injections, PA and injectate temperatures were sampled 20 times per second for 55 s. The on/off status of the electrocautery was recorded concurrently with the temperature samples, and electrocautery was not used during the TDCO measurements. Data were recorded on magnetic disks.

Analysis was done after all data for the patient had been recorded. CO was computed using an adaptation of

the Stewart-Hamilton equation[12]; a correction factor of 0.919 was used.§ The correction factor for the Spectramed catheters is different, but the difference should not exceed 6%. Areas under the temperature curve were measured using the algorithm used in the Marquette® monitors. This entails measuring the area in the initial part of the curve and a second area defined by two points on the later part of the curve. The second area is also used to estimate the area in the final portion of the curve (fig. 1). Five samples per second were used. Hardware and software performance was verified using a thermodilution simulator (Datasim 6000, Medical Data Electronics, Arleta, CA).

For analysis of the patient data, CO was calculated with and without correction for baseline drift. Because of fluctuations in the temperature, a line connecting the endpoints of the temperatures during the recording interval did not always produce a reasonable drifted baseline, and therefore a baseline was estimated for each curve. The correction for baseline drift was similar in principle to the correction method of Merrick *et al.*[3] An uncorrected CO value was calculated using an assumed flat baseline starting at the initial upstroke of the injectate curve. A corrected CO was then calculated by subtracting the baseline drift from each point in the thermodilution curve and using this adjusted curve and the same area algorithm. This calculation required the construction of an estimated drifted baseline, a straight line drawn from just before the change in temperature resulting from the CO injection to after the injectate curve appeared to be complete. The correction method is illustrated in figure 2. The estimated baseline for each CO curve was selected by two independent observers, and the resulting CO values were used to calculate the variability between observers. The average of the CO values for the two observers was used as the CO for subsequent calculations.

PA temperature–drift measurements were made independently of the baseline estimates. PA temperature drift during each CO sample recording was measured as the difference between the temperature at 1 s and the temperature at 55 s and was calculated as degrees Celsius per minute. The temperature change was treated as linear with time over this sample interval.

For all CO measurements, the thermodilution injection was done after 15 s of recording and the recording was continued for a total of 55 s. Before CPB, three CO measurements, approximately 90 s between thermodilution injections, were made and recorded after the patient was anesthetized and while the lungs were being mechanically ventilated. These closely spaced measurements were made to evaluate the technique when temperature drifts were known to be minimal and when surgical manipulation was not required, typically just after the patient had been draped. After CPB, a single injection for measurement of CO was done at three times (1, 10, and 30 min) to evaluate the effect of temperature drift on the CO measurements. Protamine and additional blood from the CBP apparatus was administered to the patient after the 1-min

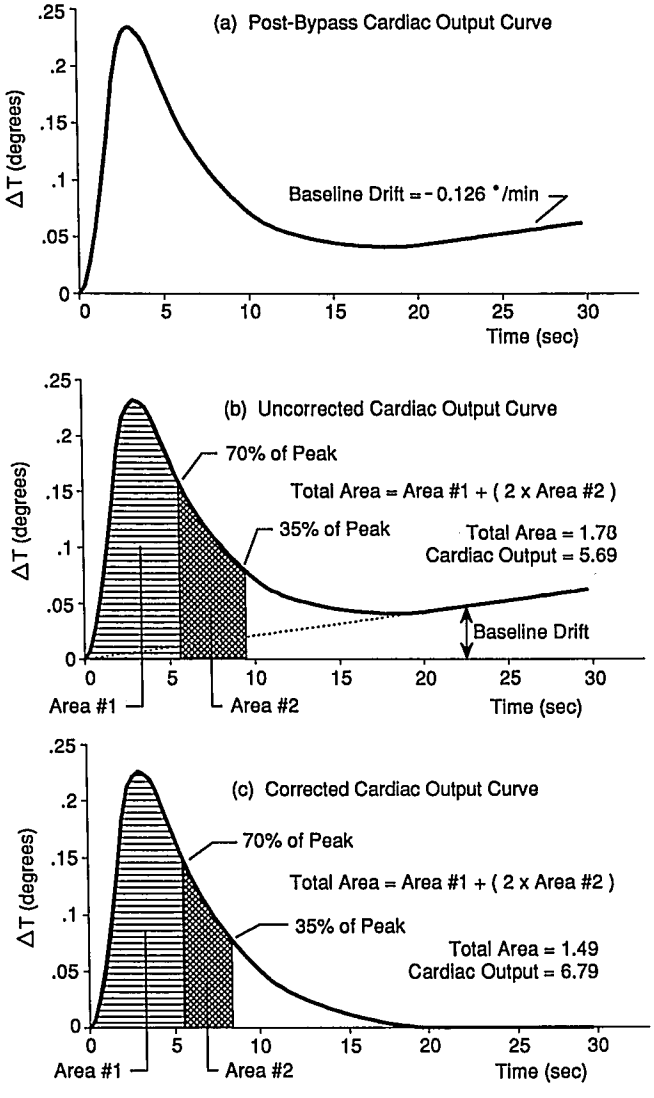


FIG. 2. Correction of the cardiac output curve for baseline temperature drift. In this drawing (*A*), the baseline drift is −0.126° C/min. An uncorrected cardiac output is computed as in figure 1, assuming a flat baseline (*B*). An actual baseline is estimated, and the difference between the estimated baseline and the flat baseline is subtracted from the cardiac output curve. This generates a corrected curve (*C*), from which a cardiac output is then calculated as in figure 1. A blood temperature of 37° C, injectate temperature of 20° C, and injectate volume of 10 ml were used for calculation.

§ Edwards Laboratories: Cardiac Output Computer Operations and Field Manual model 9520A, January 1980, p 31.

CO sample, and the volume infusions were discontinued 2 min before the 10-min sample. After the 10-min sample the residual volume from the CPB apparatus (approximately 1,200 ml) was infused intravenously. The infusion was suspended at least 2 min prior to the 30-min sample.

Descriptive statistics (means and standard deviations), significance of the PA temperature drift measurements (*t* test and repeated-measures analysis of variance), and correlation coefficients were calculated using StatView® software. Statistical analysis of the CO values (analysis of variance, paired *t* test and coefficient of variation analysis) was done using SAS® software. Because numerous comparisons were performed, a conservative probability level was chosen; each test was considered significant only if the *P* value was less than 0.01.

Results

Results for three patients were unusable because of technical problems or because the patient's intraoperative condition required deviation from the protocol. Data were analyzed for 16 patients. The average age of the patients was 63.7 ± 8.7 (± SD) yr; weight was 81.2 ± 10.0 kg. Duration of CPB was 104.5 ± 30.0 min, and patients were rewarmed for 44.1 ± 13.3 min before CPB was ended.

Times of 1, 10, and 30 min post-CPB CO samples are nominal; actual times were 1.01 ± 0.06, 10.3 ± 0.50, and 30.3 ± 0.86 min, respectively. The injectate temperature, tabulated for the 1-min postbypass sample, was 20.9 ± 0.7° C.

Temperatures during and after CPB are shown in table 1. The average maximum and minimum aortic input blood temperatures during CPB were 17.3° C and 40.1° C, not entirely reflected in the average extremes of bladder temperatures, which averaged 25.1° C at the minimum to a maximum of 36.7° C at the end of CPB. The average bladder temperature decreased by approximately 1° C in the 30 min after CPB, while the PA and pharyngeal temperatures decreased by approximately 2° C.

The rate of PA temperature change averaged over the three prebypass samples was −0.013° C/min, and there was no significant difference among the closely spaced prebypass samples. One minute after CPB the average rate of PA temperature change was −0.144° C/min, and 10 min after CPB the rate of temperature change had decreased to −0.063° C/min. By 30 min after CPB the rate of temperature change was not significant. The temperature changes are listed in table 2.

The error in CO measurements resulting from the temperature drift is expressed as the difference between corrected and uncorrected values (table 3). Repeated-measures analysis of variance for main effects showed significant differences among time points ($P = 0.003$) and between corrected and uncorrected postbypass samples ($P < 0.001$). There was also a significant difference between observers for all prebypass samples collectively (mean difference = 0.08 l/min, $P = 0.001$). None of the differences between observers was significant at any individual time.

Before CPB the temperature drift had no significant effect on the CO measurements. At 1 min after CPB, the average CO error due to temperature drift was −0.57 ± 0.52 l/min. In 7 of 16 patients the error was between 10 and 20% of the CO, and in one patient it exceeded 20%. At 10 min after CPB the average error was −0.31 l/min; in 4 patients the error exceeded 10% of CO, and in 1 patient the error exceeded 20%. The CO error was related to the rate of temperature change at 1 min ($r = 0.80$, $P < 0.001$) and at 10 min ($r = 0.63$, $P = 0.009$). At 30 min after CPB the average error was 0.13 l/min; the largest error was 9% of the CO.

For the three prebypass samples, the intersample coefficient of variation of the corrected CO (average of two observers) was 5.1 ± 2.8%. The interobserver coefficient of variation for all six samples and for both uncorrected and corrected CO ranged between 0.8 ± 1.6% and 3.0 ± 2.5%. The 1- and 10-min postbypass samples occasionally showed substantial variations in temperature apparently unrelated either to the slow temperature drifts or to the CO injection.

Graphs of temperatures and CO injections for one patient are shown as figures 3 and 4. For the first three CO injections, prebypass, there is minimal temperature drift.

TABLE 1. Intraoperative Temperatures

	Minimum during CPB	Maximum during CPB	At end of CPB	30 min after CPB
Aortic input blood	17.33 ± 2.45**	40.05 ± 0.57	38.32 ± 1.26*	
Bladder	25.11 ± 2.26*		36.70 ± 0.72*	35.76 ± 0.59*
Pharyngeal	23.11 ± 2.49		37.93 ± 0.67	35.52 ± 0.62
Pulmonary artery			37.54 ± 0.49*	35.32 ± 0.61

CPB = cardiopulmonary bypass.

Temperatures (° C) are means ± SD, for 16 patients. The 30-min post-CPB point was at 29.4 ± 1.2 min.

* A missing data point. All three bladder temperature points are missing for one patient; a thermistor urinary catheter could not be passed. Four other data points, also denoted, are missing because of electrical noise or failed connections.

TABLE 2. Rate of Pulmonary Artery Temperature Change

	Temperature Change ± SD (° C/min)	P*
Prebypass sample 1	−0.023 ± 0.019	0.0003
Prebypass sample 2	−0.008 ± 0.021	0.15
Prebypass sample 3	−0.008 ± 0.016	0.055
All prebypass samples†	−0.013 ± 0.010	0.0001
1 min postbypass	−0.144 ± 0.082	0.0001
10 min postbypass	−0.063 ± 0.057	0.0005
30 min postbypass	−0.012 ± 0.037	0.21

* Probability of temperature change = 0, two-tailed *t* test, 15 degrees of freedom. By repeated measures ANOVA for all six times, there are significant differences among times ($P = 0.0001$) but not among patients ($P = 0.55$). For the three prebypass times alone, differences are not significant (p = 0.07) among times and not significant ($P = 0.77$) among patients.

† Average of the three prebypass points, for each patient.

The 1-min postbypass sample demonstrates a temperature drift of −0.31° C, and the curve is essentially complete in 15 s. The CO was 4.9 calculated without correction, and was 6.1 when corrected for temperature drift. Ten minutes after CPB, the rate of temperature drift was −0.17° C/min; uncorrected CO was 4.7, and corrected CO was 5.9. Thirty minutes after CPB the temperature drift was minimal, and the CO was similar with and without correction.

Discussion

A systematic error in TDCO measurements produced by the rapid decrease of PA temperatures upon discontinuation of CPB is demonstrated by these data. The temperature of PA blood decreases rapidly upon discontinuation of CPB, on the average −0.14° C/min between the 1st and 2nd min after CPB. This PA temperature change is large enough to distort the thermodilution curve; the average error 1 min after CBP in this series is −0.57 l/min (11% of the average CO), and the error was as large as −2.0 l/min. The rate of PA temperature change and the associated error decrease with time, and at 30 min both the rate of temperature change (−0.01° C/min) and the CO error (−0.13 l/min or 2%) were small.

We believe that these findings apply generally. The post-CPB PA temperature decreases in our patients were similar to the PA temperature changes observed by Ralley *et al.*[8] Adequacy of rewarming in this series was judged by the bladder temperature and the duration of rewarming; the duration of rewarming was similar to that of other published series.[7–9] Redistribution of heat among areas of the body provides an explanation for the decrease in PA temperature after CPB.[7–9,13,14] The rapidly perfused tissues may be nearly at the temperature of the warm input blood from the CPB apparatus at the end of rewarming, but the slowly perfused areas may be much colder. When the input of warm blood ceases at the end of CPB, the PA temperature decreases as the rapidly perfused areas lose heat to the cooler portions of the body. The postbypass temperature decrease has been of concern, but there is no simple solution for the problem. Longer periods of warming have diminishing effects,[9,10] and the duration of rewarming must be balanced against the risks of extending the duration of CPB.

Our TDCO calculations were made using a specific algorithm to estimate the final portion of the thermodilution curve. There are at least two other similar algorithms in use[4]; these algorithms use the same principle and will be subject to similar error in the presence of baseline temperature drift. The methods produced good reproducibility for the prebypass measurements, as measured by the coefficient of variation of 5.1%. This coefficient of variability is comparable to the values of 4.4%[10,15] obtained in other series. Because of the rapidly changing conditions soon after CPB, the measurements after CPB cannot be evaluated by examining the agreement among duplicate or triplicate determinations. There is an apparent increase in the temperature "noise" after CPB, and we suspect that TDCO measurements soon after CPB are less reproducible than before CPB. We did not specifically study the increased baseline noise that occurs in the PA traces after CPB. The noise may be due to larger differences post-CPB in the temperature of the venous blood from different areas. Changes in the ratio of various sources of venous return caused by ventilation[11]

TABLE 3. Cardiac Outputs, With and Without Correction for Temperature Drift

	Uncorrected	Corrected	Difference			
			Mean	Minimum	Maximum	P*
Pre-CPB 1	3.82 ± 0.54	3.82 ± 0.57	−0.01 ± 0.08	−0.15	0.15	0.75
Pre-CPB 2	3.75 ± 0.45	3.82 ± 0.46	0.08 ± 0.20	−0.10	0.75	0.15
Pre-CPB 3	3.83 ± 0.65	3.84 ± 0.66	0.01 ± 0.07	−0.10	0.20	0.50
1 min post-CPB	4.42 ± 1.03	4.98 ± 1.23	0.57 ± 0.52	−0.05	2.00	0.001
10 min post-CPB	5.05 ± 1.10	5.36 ± 1.02	0.31 ± 0.36	−0.15	1.20	0.003
30 min post-CPB	5.15 ± 0.93	5.28 ± 0.91	0.13 ± 0.14	−0.10	0.40	0.001

Output values are liters per minute ± SD. Each cardiac output measurement is the mean for two observers; data shown are the averages for 16 patients.

* Two-tailed probability that the difference is zero, by paired *t* test.

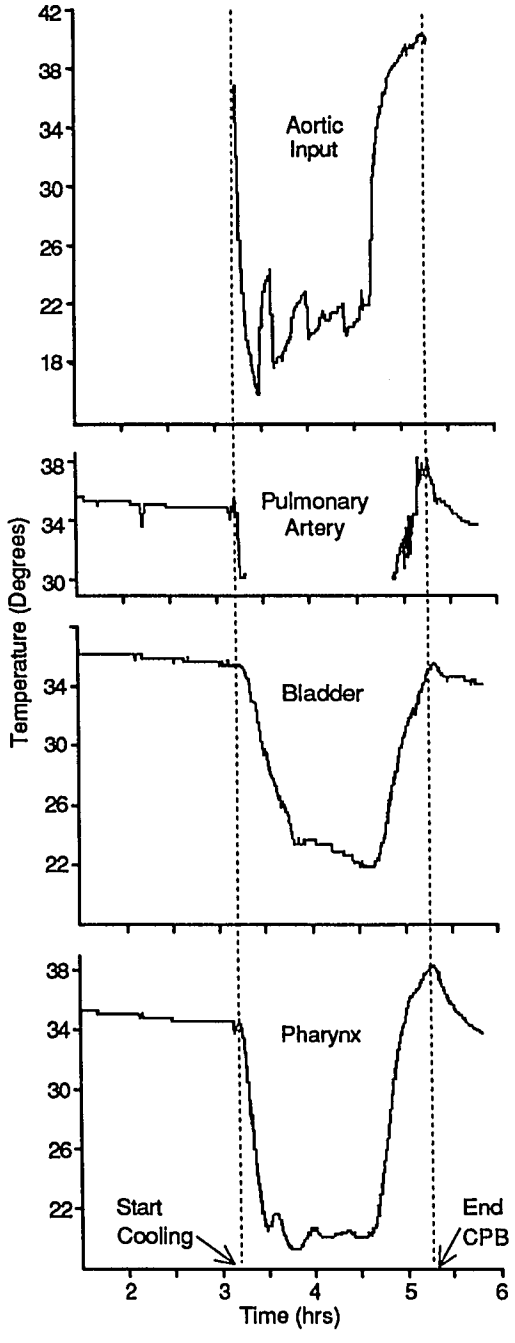


FIG. 3. Intraoperative temperatures for one patient. Temperature traces begin 1.5 h prior to CPB and end 30 min after CPB, except aortic input blood temperature, which is measured only during CPB. Pulmonary artery temperature was not measured and is not plotted below 30° C. Points on the pulmonary artery and aortic input blood temperature traces concurrent with electrocautery use were not plotted to minimize error from electrical noise.

or by surgical manipulation would then cause exaggerated temperature fluctuations.

Examination of the curves and the underlying basis of the postbypass CO error related to PA temperature drift suggests that the error will be affected by several aspects of monitoring practices and clinical management. More effective rewarming should reduce the rate of PA temperature decrease after CPB. The CO measurement error due to temperature drift also can be reduced by the use of cold or iced injectate rather than room-temperature injectate. Comparison of room-temperature and iced injectate showed no advantage to the use of iced injectate in several clinical studies.[16-18] However, the use of iced injectate will produce a thermodilution curve that is larger relative to the temperature drift, and when the PA tem-

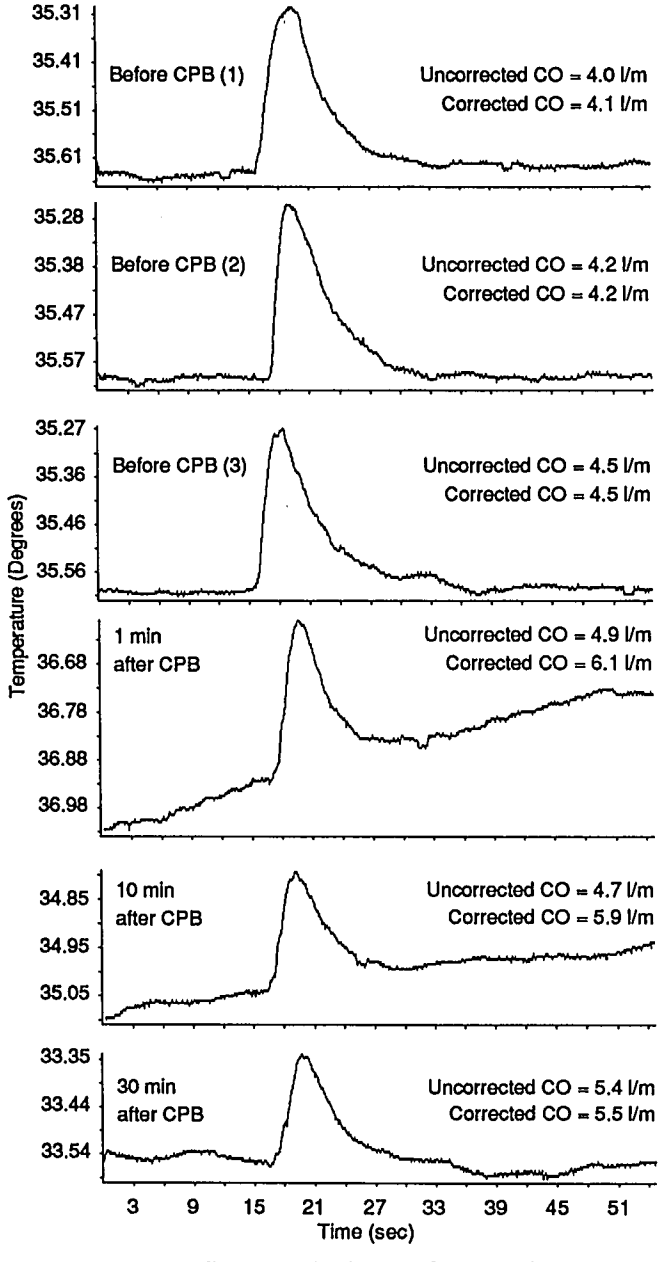


FIG. 4. Cardiac output (CO) curves for one patient.

perature is not stable there should be an advantage to the use of iced injectate.[19] Problems associated with the use of iced injectate include potential contamination of iced syringes and technical error in estimating injectate temperature,[17,18] but closed injectate assemblies with in-line thermistors can make the use of iced injectate more practical. We speculate that the profile of the aortic input blood temperature during rewarming also may have an effect: if the input blood temperature is reduced to 37° C for several minutes prior to ending CPB, the difference between the PA temperature and the cooler areas might be minimized.

Conceivably, baseline correction for individual CO curves could be made to correct CO measurements for clinical use, but such corrections would be difficult to automate. Errors resulting from PA temperature drift should be a larger proportion of the CO in thermodilution curves that cover a longer time or that have a smaller change in temperatures. Thus there will be no simple relationship between the rate of baseline temperature change and the error in CO. Baseline temperature drift is readily detected by examination of the CO curves, and although it may not be possible to obtain accurate measurements in some circumstances, incorrect data can be avoided by accepting only CO curves that begin and end on a stable baseline.

The authors thank Michael Lapic for programming and other technical assistance and thank Christine Skibinski, M.S. for assistance with the statistical analysis.

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