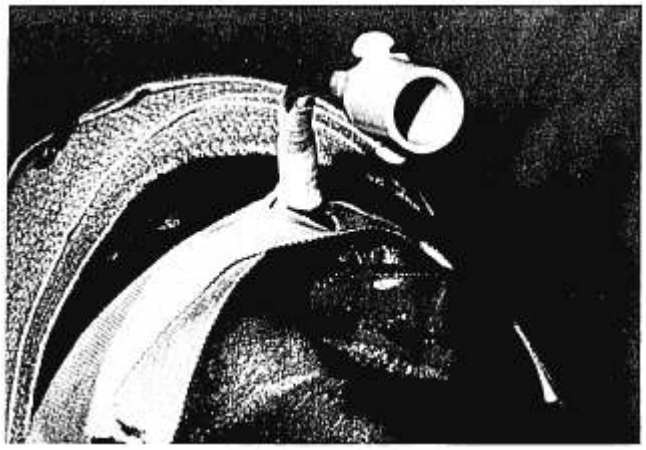

FIG. 1. Patient in recovery room after nasal intubation. Note markedly swollen tongue extruding from mouth.

assessment of the airway should be made before extubation of the trachea is considered to ensure that facial or tongue edema has not occurred. Furthermore, our case demonstrates that despite these measures, postanesthetic lingual swelling with airway obstruction still can occur.

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Major Errors in Thermodilution Cardiac Output Measurement during Rapid Volume Infusion

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Thermodilution measurement of cardiac output has become a cornerstone of hemodynamic monitoring in anesthesia and critical care medicine.[1,2] Understanding the theory of the thermodilution technique and the assumptions underlying this theory is necessary to avoid several sources of error inherent in this technique. For example, thermodilution cardiac output measurements can be influenced by respiratory variations,[2,3] the volume and temperature of injectate,[4,5] the patient's temperature,[6,7] and other physical characteristics of the measurement system.[2,3,8,9] Recently, we observed marked variations in thermodilution cardiac output measurements in patients following open heart surgery while they were receiving intermittent rapid iv fluid infusions via a peripheral iv catheter. Whereas alterations in the volume or temperature of the injectate obviously influence the accuracy of thermodilution measurement of cardiac output,[2,4,5] the effect of concurrent peripheral iv volume infusions has not been reported previously. Theoretically, small fluctuations in blood temperature caused by peripheral infusions could cause major errors in cardiac output measurements. The following protocol was designed to determine if rapid volume infusion into a peripheral vein altered the accuracy of thermodilution measurement of cardiac output and to quantitate the magnitude of this error in a clinically relevant situation.

METHODS

Fourteen patients, ages 42–76 yr, prospectively were studied following discontinuation of cardiopulmonary bypass for cardiac surgery. Approval of our Committee on Clinical Investigation and informed consent of individual patients was obtained prior to surgery. Routine monitoring required for the operative management of these patients included insertion of an arterial cannula and a triple-lumen Swan-Ganz® catheter for the determination of thermodilution cardiac outputs. The patient's monitoring or management was not altered for the purpose of this study.

The thermodilution cardiac output was determined in the standard fashion using a Lyons® (Electronics for Medicine Model #TCCO-04) cardiac output computer while simultaneously recording the analog output of the thermodilution curve. The computer was calibrated at the beginning of the case and prior to discontinuing cardiopulmonary bypass. Cardiac outputs were determined in the standard fashion with the injection of 10

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Key words: Measurement techniques: thermodilution cardiac output.

ml iced saline via the central venous port of an Edwards® Swan-Ganz thermodilution pulmonary artery catheter. The temperature of the iced saline was monitored continuously and was maintained between 0 and 1° C. These catheters were inserted through an internal jugular vein with continuous pressure monitoring to confirm their pulmonary artery location. At no time during the study protocols was the catheter position altered.

Following chest closure, but prior to skin closure, during periods of relative hemodynamic stability, a series of thermodilution cardiac output measurements were made during alternating control and infusion conditions. The time required to perform these measurements was 5–10 min. The patient's core temperature was 33–37° C. During control measurements, no iv fluids were infused. During test measurements, rapid-volume infusion was provided by simulating the clinical situation of rapid volume supplementation by a squeeze bulb incorporated into the iv line (Abbott® No. 8949). Approximate volume delivered by one compression of the bulb was 30–45 ml. Volume was infused through a 14- or 16-gauge, 2½-inch-long catheter (Angiocath®) located in the wrist or forearm. Two different infusion protocols were investigated. For protocol 1, three to five compressions of the bulb were made starting just prior to initiation of the cardiac output measurements. With protocol 2, three to four compressions of the bulb were made and the temperature change in mixed venus blood induced by the infusion monitored. When this change had plateaued (usually about 20 s after the infusion was begun), the cardiac output measurement was initiated. For protocol 1, both room temperature (cold, 17–20° C) and warmed (Fenwal® Blood Warmer, 30–36° C) fluids were used. Each test measurement of cardiac output made with infusions was determined between two control measurements made immediately before and after the test measurement. Results are expressed as mean ± the standard deviation. Student's *t* test was used to compare data. As the control measurements were not different before and after the test infusion, we compared the test results with the mean of the before and after cardiac output measurements.

Results

For the cardiac output measurements determined with infusion protocol 1, there were 32 data pairs using cold infusion and 12 data pairs using warm infusion. The mean of all control cardiac output measurements before (5.53 ± 1.08 l/min) and after (5.65 ± 1.11 l/min) the test infusions were not different. The mean of the control measurements for the cold infusions was 5.85 ± 1.0 l/min. For test measurements made in proximity to the cold infusions, calculated outputs were 3.11

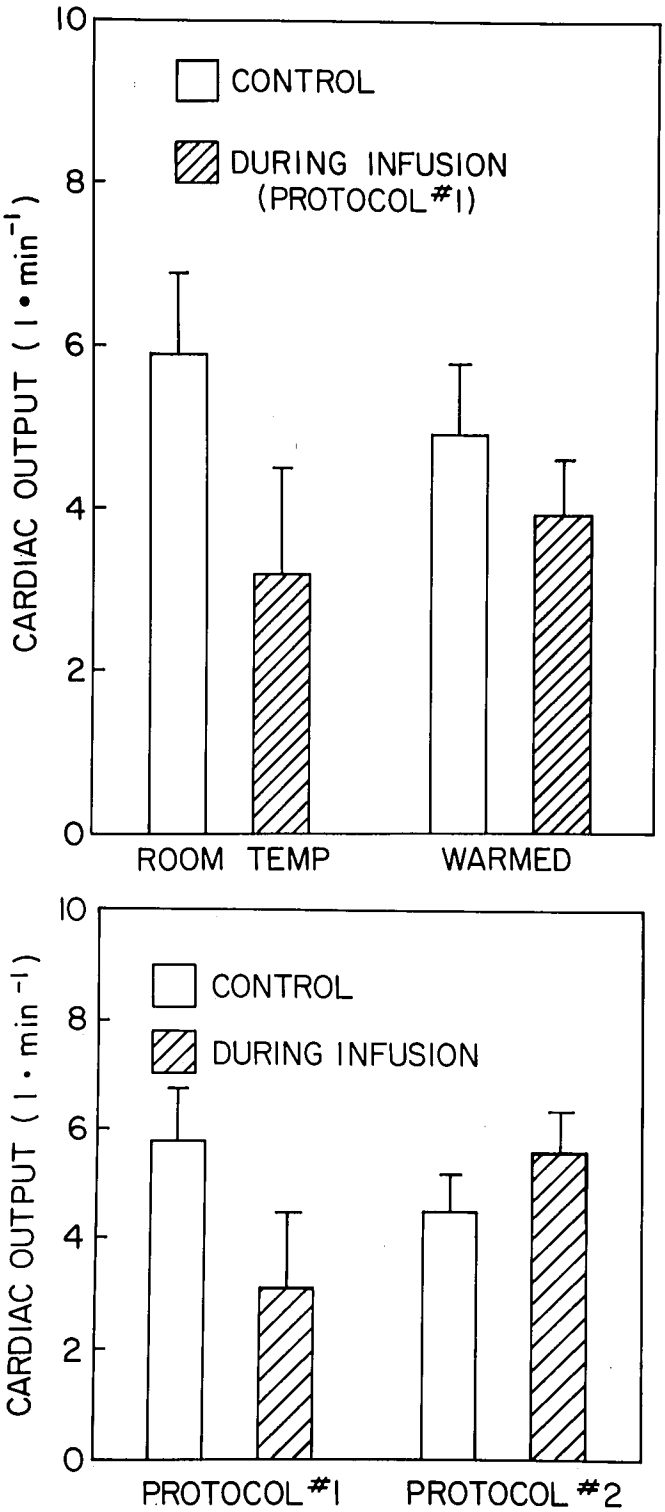

FIG. 1. *A.* Cardiac output on the ordinate in liters per minute for each experimental condition (standard deviations shown by brackets). Control for both warmed and room temperature are compared with the means for measurements with rapid volume infusion by protocol 1. *B.* Results with the two different infusion protocols (room temperature fluids). Measurements with protocol 1 are reduced from controls, whereas measurements with protocol 2 are increased from controls.

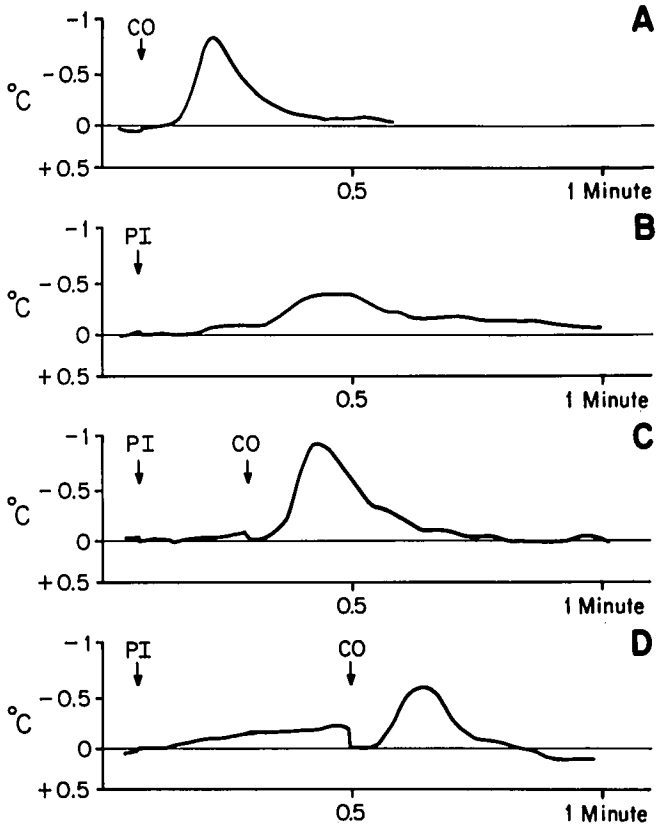

FIG. 2. Temperature curves from thermodilution output computer. CO = start of cardiac output measurement (followed by injection of iced saline); PI = start of peripheral volume infusion. *A.* Normal curve (TCDO = 3.21 l/min). *B.* Curve from peripheral volume infusion alone. *C.* Injection of iced saline just after start of peripheral volume infusion (TDCO = 2.18 l/min). *D.* Injection of iced saline approximately 20 s after peripheral volume infusion (TDCO = 4.52 l/min).

± 1.43 l/min ($P < 0.001$) (fig. 1*A*). Using warm infusions, the mean of the control measurement was 4.93 ± 0.89 l/min, *versus* 3.96 ± 0.82 l/min for the test measurements ($P < 0.001$). The range of per cent decrease in measured cardiac output with cold infusion was 30–80% of the control measured value. During warm infusions, this decrease from control value was from 20% to 40%.

Ten data pairs were obtained using infusion protocol 2. In contrast to the above results, cardiac outputs made in proximity to infusions by this protocol (5.59 ± 0.67 l/min) were greater than corresponding control measurements (4.51 ± 0.69 l/min) (fig. 1*B*) ($P < 0.001$). The range of increase was 11–42%.

DISCUSSION

These results demonstrate clinically significant errors in the measurement of cardiac output by thermodilution during periods of intermittent rapid iv volume infusions through a peripheral vein. The outputs measured in proximity to infusions ranged from 20% to 140% of control measurements. The reason for this source of error can be understood by examining the thermodilution equation.

The equation for the determination of cardiac output by the thermodilution technique[2,10] can be expressed as:

$$\text{cardiac output} = \frac{k(T_i - T_{bs})}{\int_0^\infty (T_t - T_{bs})dt}$$

where T_i is the injectate temperature, T_{bs} is the reference baseline blood temperature, T_t is the temperature measured at the catheter tip as a function of time, and k is a constant that takes into account the heat capacity of the injectate solution and blood, the volume of the injectate, and an estimate of heat gain from external sources. The denominator is equal to the area under the temperature curve (inversely related to cardiac output). The final 30% of this curve usually is extrapolated by an exponential fit based on the initial 60–70% of the decay in this curve to avoid errors caused by recirculation of injectate.[2,3] During clinical application of this technique, T_{bs} is measured at the catheter tip just prior to the injection of the iced injectate and then is assumed to remain constant over the subsequent measurement period, *i.e.*, all subsequent variations in temperature at the catheter tip are assumed to be due to the iced injectate. Should changes in T_{bs} occur (*i.e.*, changes in blood temperature not due to the iced injectate), resultant errors may appear, not only in the numerator and denominator of the basic equation, but also from improper exponential extrapolation of the temperature curve and violation of other assumptions regarding heat gain from external sources inherent in the factor "k." For small variations in T_{bs}, the predominant error will appear in the denominator (area under the curve) as can be predicted from the relative magnitudes of both T_i and T_t with respect to T_{bs}. The magnitude and direction of this error will depend on the amount and timing of the fluctuations in T_{bs}. The magnitude of these fluctuations will depend in turn on the rate and volume of infusion, patient size, temperature, cardiac output, and the location of the infusion site.

In our series, the predominant effect observed with infusion protocol 1 was a decrease in the calculated cardiac output resulting from an artifactual increase in the area under the thermodilution temperature curve. This is illustrated graphically by the actual temperature recordings from patients as seen in figure 2. The change in temperature recorded by the catheter thermistor due to an iced saline injection to measure cardiac output is shown in figure 2*A*. This is a normal thermodilution

curve. The temperature curve resulting solely from rapid volume infusion through a peripheral catheter is shown in figure 2*B*. With infusion protocol 1, the temperature curve obtained during the measurement of cardiac output is like that seen in figure 2*C*. It can be seen that this represents the summation of the curves in figures 2*A* and *B*. The result is a larger calculated area for the thermodilution curve and, hence, a reduced value for the derived cardiac output. This effect is illustrated diagramatically in figure 3*A*. This result occurs with both the room temperature infusions and the warmed infusions, as even the warmed infusions were below body temperature. The magnitude of error is less with the latter, however, because infusate temperature is closer to body temperature and consequently causes less change in mixed venous blood temperature.

A decrease in measured cardiac output is not, however, the only possible result from intermittent rapid volume infusion. The timing of the rapid volume infusion and, hence, the timing of fluctuations in T_{bs} is also an important factor. This fact is brought out by the results using infusion protocol 2 and is illustrated in figures 2*D* and 3*B*. With this protocol, the start of the cardiac output measurement was made to coincide with the peak of the temperature curve due to the peripheral volume infusion. The temperature recorded at this instant now becomes T_{bs} for the subsequent measurement. The sharp drop in the curve occurring after the initial slow rise due to the peripheral infusion is caused by automatic "re-zeroing" of the computer. The change in temperature resulting from the peripheral infusion (dashed line in figure 3*B*) now "falls" below this new reference baseline and acts to reduce the change in temperature caused by the iced saline injection. This results in a reduction in the calculated area under the curve and an increase in the derived cardiac output.

Although these effects can be readily predicted from understanding the termodilution theory, the magnitude of this response is somewhat surprising. We found maximal variations of up to 80% in measured cardiac output during the intermittent rapid infusion of room temperature crystalloid solutions. Clearly, measurement errors of this magnitude can be profoundly misleading. Since these errors are related to fluctuations in baseline blood temperature caused by peripheral infusions, rapid volume infusions either should be maintained at a constant rate or discontinued for at least 30 s prior to measurement of cardiac output by the thermodilution technique.

The authors thank Professor Mark C. Rogers, M.D., for his helpful comments and guidance in the preparation of this manuscript and Nancy Martin for her excellent secretarial assistance.

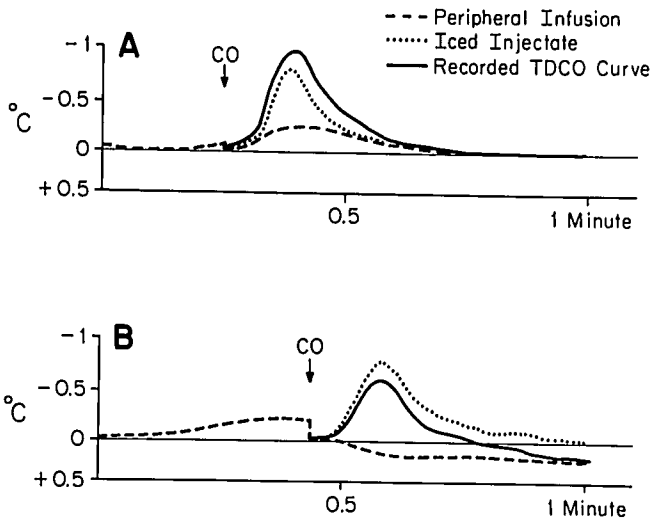

FIG. 3. Diagramatic representation of effects of peripheral volume infusion on temperature curve. Peripheral volume infusion was started at time = 0. CO = start of cardiac output measurement (followed by iced saline injection). *A*. Temperature change caused by peripheral volume infusion augments measured change following iced saline injection. *B*. Temperature change caused by volume infusion decreases measured change following iced saline injection (notice effect of "rezeroing" referenced baseline temperature at CO).

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