Overestimation of Pediatric Cardiac Output by Thermal Indicator Loss

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SUMMARY The accurate measurement of pediatric cardiac output by thermodilution requires that the quantity of cold indicator introduced into the central circulation be known. This study defines an important source of error in the correction factor for the amount of heat gained by small volumes of cold injectate during passage through pediatric catheter systems. This error may result in significant overestimation of cardiac output (as much as 59%) when blood at body temperature is withdrawn into the injection lumen of the pediatric catheter before the injection.

THERMODILUTION catheter systems, both adult and pediatric, should account for the amount of heat gained (C_T) by the cool injectate as it passes through a lumen of a catheter warmed to body temperature.

The C_T factor is incorporated into the formula for cardiac output by thermodilution (see appendix) and a table of C_T values for various injectate volumes and temperatures is constructed that is specific for a given catheter type and size. Usually, injectate temperature, patient body temperature and C_T are entered as constants into a thermodilution cardiac computer.

A common method for measuring and computing C_T includes the volume of the catheter dead space as part of the total injectate volume. This method was first described and used with the adult #7F flow-directed thermodilution catheter and later with the smaller pediatric catheter systems. However, the dead space of the injection lumen of the adult #7F catheter is 0.8 ml (8% of a 10-ml injection), whereas in the smaller #5F pediatric catheter system the dead space is approximately 0.65 ml (65% of a 1-ml injection). This observation led to the investigation of the effect that temperature of the dead space fluid has on the C_T value supplied by the catheter manufacturer, because many investigators recommend prefilling the injection catheter with blood at body temperature and others do not.1, 7-11

Materials and Methods

Two catheter systems (Edwards Laboratories) were studied. The first was a #5F, 60-cm, flow-directed catheter with four lumens: one for measuring pressure at the catheter tip, one for measuring pressure and injecting cool solution through an opening 15 cm proximal to the catheter tip, one for balloon inflation and one that contained lead wires to a thermistor. The second catheter system consisted of a #2F thermodilution catheter (designed to be inserted through the right ven-

tricular wall and manipulated into the pulmonary artery during thoracotomy for cardiac surgery) and a #3.5F injection catheter, 30 cm long, separately placed into the right atrium.

A model was used to measure C_T (fig. 1). A heated, stirred 10-liter water bath was maintained at a temperature of 37 ± 0.2°C. Ten centimeters of the #3.5 F catheter and 25 cm of the #5F catheter were immersed in the water bath, with the tip brought out and inserted into a small plastic bag for collection of the injectate. The #5F catheter was cut at the level of the proximal injection port and the distal 15 cm of catheter was discarded so that the injection port could be inserted into the plastic bag. The immersion lengths above represent the intravascular segment of catheter exposed to body temperature and are those specified by the manufacturer.

The plastic bags were made from long, thin tubes of polypropylene, 1 or 3 cm in diameter, cut to size for a given injection volume and heat-sealed at the bottom. They were secured outside the water bath with a laboratory clamp. A standard Luer-Lok plastic stopcock was attached to each catheter and its volume was included in all measurements.

Iced injectate was prepared by drawing the desired volume of 5SW into 5-ml syringes and placing them in crushed melting ice in an insulated container for 20 minutes. Room temperature injectate was maintained at 24 ± 0.5°C with a small heater stirrer. All injectate temperatures (T_I) were monitored with a separate calibrated thermistor probe connected to a cardiac output computer (Electronics for Medicine).

For the temperature measurement of the delivered injectate, a low-mass, fast-responding thermistor with a measured time constant of 110 msec was connected to a thermodilution bridge (Electronics for Medicine) and calibrated from 0-25°C in 1°C intervals with a laboratory thermometer accurate to 0.1°C. The thermistor was inserted into the plastic bag. Care was taken during measurement to keep it centered in the liquid. The analog output of the thermistor bridge was recorded on an ink recorder. Upon injection of cool solution through a given catheter into the plastic bag, the equilibration of temperature of the delivered injectate as measured by the thermistor was recorded. Equilibration occurred in less than 1 second and the reading remained stable for about 10 seconds before

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there was a rise in fluid temperature from exposure to air at ambient temperature. This stable reading was recorded as the average temperature of the delivered injectate (T_ID).

We determined (and subtracted from T_ID) the amount of heat gained by the injectate from the measurement apparatus itself (T_K), i.e., the small plastic bag and thermistor. Before and after each set of C_T measurements for a given catheter, injectate volume and temperature, an identical volume of injectate was directly introduced into the small plastic bag with a syringe at injectate temperature. The temperature of the directly delivered injectate (no catheter) was measured and recorded as T_K. The largest T_K was 0.8°C for the 1 ml, 0°C injectate and the variability of the T_K measurements (before and after a given set of C_T measurement) was less than 0.1°C.

C_T was calculated from the formula

\[
(T_B - T_ID - T_K) / (T_B - T_I)
\]

where T_ID is the mean temperature of the injectate delivered for a given volume at the injection site (including the catheter and stopcock dead space), T_K is the amount of heat gained by the injectate from the measurement apparatus, T_B is the temperature of the water bath and T_I is the temperature of the injectate just before injection.*

C_T measurements were performed with each catheter system at injectate temperatures of 0 ± 0.1°C (iced) and 24°C ± 0.5°C (room temperature). At 0°C, injectate volumes of 1, 2, 3 and 5 ml were collected and measured for the #35F catheter, and injectate volumes of 1, 2 and 5 ml for the #3.5F catheter. At 24°C temperature, injectate volumes of 1, 2 and 5 ml were collected and measured for each catheter.

Two series of C_T measurements were made. In the first series, at each injectate volume and temperature, at least 5 C_T determinations were performed by prefilling the dead space of the catheter to be tested with 1 ml of injectate (either 24°C or 0°C), waiting 20 seconds, and injecting as rapidly as possible. The delivered injectate volume was collected and its temperature measured. The fluid from prefilling was not collected in the small plastic bag, but was injected into the water bath.

In a second series, five more C_T determinations were done with the catheter dead space prefilled with 1 ml of 37°C injectate. In this way, the effect on C_T by prefilling the injection catheter dead space with body temperature fluid at 37°C or injectate temperature fluid before actual injection could be quantitated and compared to the C_T value supplied by the manufacturer.

The following terms are used:

C_T(I) — the average of C_T measurements with the catheter dead space prefilled with 1 ml injectate temperature fluid for a given volume and injectate temperature.

C_T(37) — the average of C_T measurements with the catheter dead space prefilled with 1 ml of DSW at 37°C for a given volume and injectate temperature.

C_T(M) — the C_T value supplied by the catheter manufacturer for a given volume and injectate temperature.

Results

The C_T(I) determinations measured in this study agreed with the C_T(M) values at almost all injectate volumes for the #3.5F and #35F catheter systems. The largest differences between C_T(I) and C_T(M) were with the #3.5F catheter at 1- and 2-ml volumes of 0°C injectate, resulting in differences of 4.7% and 3.2%, respectively. All other C_T(I) vs C_T(M) differences were 1.2% or less (table 1).

The difference measured between C_T(37) and C_T(M) was much greater at all injection volumes for both 24°C and 0°C injectate temperatures than at those measured between C_T(I) and C_T(M) (table 2). The largest differences were with the #35F catheter: 0°C injectate at volumes of 1 and 2 ml, 59.1% and 25.9% respectively; and 24°C injectate at volumes of 1 and 2 ml, 29.0% and 18.6%, respectively.

The difference between the values for C_T(I) and C_T(37) with each catheter, injectate volume and temperature were tested for statistical significance. The #3.5F catheter, 0°C injectate at 2 ml volume gave the only value that was not significant \(p < 0.20\); the difference was significant at 5 ml \(p < 0.05\). All other comparisons of C_T(I) and C_T(37) were significant \(p < 0.01\).

Discussion

Thermodilution can be performed by withdrawing blood at body temperature either before or after the injection.1-11 Goodyer et al.6 and Fronek and Ganz2 recommended withdrawing blood at body temperature before injection so as to avoid mixing of the injectate with fluid at some unknown temperature intermediate between body temperature and that of the previous injection. For a specific injection catheter in a body at constant temperature, the amount of heat gained for a given injectate volume can only be con-
stant if the initial conditions, i.e., the temperature and volume of the dead space of the injection catheter, are the same for each determination.

Ganz and Swan\(^1\) described the variability of \(C_T\) for the adult \#7 F flow-directed thermodilution catheter. They reported that \(C_T\) was relatively constant (within 3\%) for injection rate (2-4 ml/sec), body temperature (35-39°C) and intravascular catheter length (25-45 cm). Only \(C_T\) at 0°C with a 10-ml injectate volume was measured, and it was not stated whether the catheter dead space was prefilled with 0°C or 37°C D5W. They did, however, recommend withdrawing blood at body temperature after the injection of cold indicator.

Meisner et al.\(^7\) described withdrawing blood at body temperature after injection to minimize a cooling effect (which prolongs the downslope of the descending limb of the thermodilution curve) from the cold injectate remaining in the catheter lumen. The errors introduced by this cooling effect were small; nevertheless, Meisner et al. recommended warm withdrawal of blood after injection to improve accuracy. However, if cardiac output measurements were done in duplicate or triplicate using the catheters and \(C_T(M)\) in this study, and following the recommendation of Meisner et al., the second and third determinations would overestimate \(Q\) by the percent difference listed in table 2.

Large, significant differences occur between \(C_T(37)\) and \(C_T(M)\), differences that do not exist between \(C_T(I)\) and \(C_T(M)\) when the injection rate, body temperature, injectate temperature and catheter immersion length are held constant. This difference between \(C_T(37)\) and \(C_T(M)\) increases as injectate volume and temperature decrease for each catheter. \(C_T(M)\) and \(C_T(I)\) were determined by a similar technique, i.e., when \(C_T\) was measured by the manufacturer, the injection lumen was prefilled with injectate temperature fluid as this is a simpler and faster technique to perform in the laboratory.

The overestimation of cardiac output from using \(C_T(M)\) and prefilling the catheter with blood at body temperature for all measured injectate temperatures and volumes with \#5 F and the \#3.5 F catheters is listed in table 2. For example, if a \#F catheter similar to the one used in this study were inserted into a pediatric patient, an injectate volume of 2 ml, 0°C D5W used and \(C_T(M) = 0.729\) are entered as constants into a cardiac output computer. If the injection catheter is prefilled with blood at body temperature and the injectate then delivered within 20 seconds, the

TABLE 1. Catheter Dead Space Prefilled with 1 Milliliter of D5W at 0°C or 24°C

<table>
<thead>
<tr>
<th>Catheter</th>
<th>Vol</th>
<th>(T_i)</th>
<th>n</th>
<th>(C_T(I))</th>
<th>SD</th>
<th>(C_T(M))</th>
<th>%Diff</th>
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<tr>
<td>#3.5F</td>
<td>1.0</td>
<td>0</td>
<td>6</td>
<td>0.804</td>
<td>0.010</td>
<td>0.842</td>
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<td>2.0</td>
<td>0</td>
<td>5</td>
<td>0.867</td>
<td>0.013</td>
<td>0.895</td>
<td>3.2</td>
</tr>
<tr>
<td>0°C D5W</td>
<td>5.0</td>
<td>0</td>
<td>5</td>
<td>0.916</td>
<td>0.004</td>
<td>0.927</td>
<td>1.2</td>
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<td>#5F</td>
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<td>0</td>
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<td>0.571</td>
<td>0.012</td>
<td>0.571</td>
<td>0.0</td>
</tr>
<tr>
<td>prefilled</td>
<td>2.0</td>
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<td>0.009</td>
<td>0.729</td>
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<td>0.003</td>
<td>0.792</td>
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<td>0.017</td>
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<td>0.010</td>
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<td>24°C D5W</td>
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<td>24</td>
<td>5</td>
<td>0.948</td>
<td>0.008</td>
<td>0.956</td>
<td>0.8</td>
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<td>#5F</td>
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<td>-0.3</td>
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Abbreviations: \(T_i =\) injectate temperature; \(C_T(I) =\) average amount of heat gained in study prefilling catheter with 1 ml of D5W at 0°C or 24°C; \(C_T(M) =\) average amount of heat gained as value determined by manufacturer; %Diff = \((C_T(M) - C_T(I))/C_T(I)\).

TABLE 2. Catheter Dead Space Prefilled with 1 Milliliter of D5W at 37°C

<table>
<thead>
<tr>
<th>Catheter</th>
<th>Vol</th>
<th>(T_i)</th>
<th>n</th>
<th>(C_T(37))</th>
<th>SD</th>
<th>(C_T(M))</th>
<th>%Diff</th>
</tr>
</thead>
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<td>0</td>
<td>7</td>
<td>0.760</td>
<td>0.012</td>
<td>0.842</td>
<td>10.8</td>
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<td>4.4</td>
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<tr>
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<td>5</td>
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<td>0.792</td>
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<td>0.927</td>
<td>0.012</td>
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<td>0.774</td>
<td>0.010</td>
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<td>7.1</td>
</tr>
</tbody>
</table>

Abbreviations: \(T_i =\) injectate temperature; \(C_T(37) =\) average amount of heat gained in study prefilling catheter with 1 ml of D5W at 37°C; \(C_T(M) =\) amount of heat gained determined by manufacturer; %Diff = \((C_T(M) - C_T(37))/C_T(37)\).
value calculated by a cardiac output computer will overestimate \( Q \) by 25.9\%. This error will be reproducible in a series as long as the catheter is prefilled with blood at body temperature before each determination. Many of the errors are in a range that would be clinically important in management of the pediatric patient as well as statistically significant in small animal research.

Requirements for the accurate measurements of thermodilution cardiac output in the pediatric patient for the two catheter systems used in this study are: (1) Preaspiration of blood at body temperature should not be done. (2) The catheter lumen should be filled with 1 ml of the injectate temperature fluid, and after a 20-second delay, the desired volume of injectate should be injected as rapidly as possible. (3) Do not withdraw blood at body temperature after the injection. (4) Use the values for \( C_T \) supplied by the catheter manufacturer. (Catheters by other manufacturers may yield different results.) (5) Serial cardiac output determinations may be repeated as soon as the temperature baseline is stable and 20 seconds has passed, as the injection lumen is prefilled with injectate temperature fluid from the previous injection. The above injection technique provides the precise delivery of a known amount of thermal indicator, is clinically easy to perform and repeat, and improves the accuracy and reproducibility of pediatric cardiac output measurements.

Acknowledgment

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References


Appendix

\[
Q = \frac{1.08 \, (T_n - T_1) \, V \, C_T \, 60}{\int_0^\infty \Delta T_n(t) \, dt}
\]

where \( Q \) = cardiac output (l/min); \( T_n, T_1 \) = temperature of blood and injectate (°C); \( V \) = volume of the injectate (l); \( C_T \) = correction for the amount of heat gained by injectate during injection; 1.08 = correction for the specific heat and gravity of blood and injectate; \( \int_0^\infty \Delta T_n(t) \, dt \) = integral of the resultant temperature-time curve (°C · sec); 60 = factor for conversion of l/sec to l/min.
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