Improved Accuracy and Precision of Thermodilution Cardiac Output Measurement Using A Dual Thermistor Catheter System

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OBJECTIVES
To assess whether thermodilution cardiac output determination based on measurement of injectate temperature in vivo leads to more accurate and precise estimates and to study the influence of chilled injectate on test performance.

BACKGROUND
Cardiac output measurement via right heart catheterization is used extensively for hemodynamic evaluation in a variety of diagnostic, perioperative and critical care settings. Maximizing accuracy is essential for optimal patient care.

METHODS
This prospective study of 960 thermodilution cardiac output measurements was conducted using conventional and dual thermistor techniques. Specialized dual thermistor right heart catheters were constructed using a second thermistor positioned to measure injectate temperature in vivo just prior to entry into the right atrium. To eliminate interinjection variability, a custom set-up was developed that permitted output measurement using both techniques simultaneously. Both ambient temperature injections and cooled injections were investigated.

RESULTS
The dual thermistor technique demonstrated significantly less measurement variability than the conventional technique for both ambient temperature (precision = 0.41 vs. 0.55 L/min, p < 0.001) and cooled (precision = 0.35 vs. 0.43 L/min, p = 0.01) injections. Similarly, the average range of cardiac output values obtained during five sequential injections in each patient was less using the dual thermistor approach (1.05 vs. 1.55 L/min, p < 0.001). The use of cooled injectate reduced the mean error of the dual thermistor technique but actually increased the mean error of the conventional technique. Even with ambient temperature injections, injectate warming during catheter transit varied considerably and unpredictably from injection to injection (2 SD range = −0.22 to 5.74°C). Conventional ambient temperature and cooled measurements significantly overestimated Fick cardiac output measurements by 0.32 and 0.50 L/min, respectively (p < 0.001). In contrast, dual thermistor measurements were statistically similar (−0.08 and −0.08 L/min, p = 0.34) to Fick measurements.

CONCLUSIONS
This new dual thermistor approach results in a significant improvement in both precision and accuracy of thermodilution cardiac output measurement. (J Am Coll Cardiol 1999;33: 883–91) © 1999 by the American College of Cardiology

Thermodilution is the most widely used technique for determining cardiac output (CO) in humans. It was introduced as a method of blood flow measurement by Fegler four decades ago (1). Routine clinical application of the technique became practical in the 1970’s with the development of bedside flow-directed right heart catheterization (2). A number of studies in both experimental animals and humans have compared the thermodilution technique with other measures of CO such as indocyanine green infusion, Fick oxygen consumption and electromagnetic flowmetry (3–11). Most have demonstrated good agreement, but concerns for important sources of error remain (5,12,13).

Critical to the technique is an accurate measurement of temperature (temp) of both blood and injectate immediately preceding injection. By the Stewart-Hamilton formula (4), the difference between these two temps (typically 16°C when using room temp injectate) is in direct proportion to CO. Hence, minor errors in either of these two measurements can have important consequences. The earliest work with thermodilution output used two internal thermistors, one positioned at the right atrial injection port and one in the pulmonary artery, to obtain this temp difference (14).
However, the proximal thermistor was soon abandoned as cumbersome, expensive and unnecessary (2,15). The error resulting from measuring injectate temp remote from the injection port site was felt to be negligible, based almost exclusively on in vitro data (2).

Improvements in technology and miniaturization have made the construction of a small caliber dual thermistor catheter both practical and inexpensive (16). This study was designed to test whether use of this new catheter system can improve either precision or accuracy of measurement during clinical use and how this relationship is affected by the choice of injectate temp. The study design included a unique set-up that permitted simultaneous measurements using the same thermodilution catheter, distal thermistor, bolus size and timing, injectate and body temp, computation algorithm, etc. This set-up helped eliminate many of the confounding variables that may have tainted prior human investigations in the field.

METHODS

Patient population. Potential participants were identified from those undergoing nonemergent cardiac catheterization (cardiac cath). Both individuals with and without definite clinical indications for right heart catheterization were included. Exclusion criteria were: 1) clinically unstable condition; 2) rhythm other than sinus; 3) more than five extra systoles per minute; 4) severe tricuspid regurgitation; 5) inability or unwillingness to grant written informed consent. The protocol was approved by the University of Washington Human Subjects Committee. Two patients were unable to complete the study, one because of his inability to tolerate the mouthpiece used for expired gas collection and the other due to inadvertent contamination of the expired gas samples.

Set-up. To avoid the inherent variability associated with serial injections in terms of injectate temp, injection rate, bolus volume, etc., a custom set-up was developed to permit measurement of thermodilution CO simultaneously using both the standard and the dual thermistor approach. An unmodified commercially available dual thermistor catheter (Dualtherm, B. Braun Medical Inc, Bethlehem, Pennsylvania and Lyons Medical Corp., Sylmar, California) was used. The excitation voltage driving the distal temp sensor (thermistor) originated from a single CO computer. The returning signal, though, was electrically split to permit simultaneous input into two CO computers, both using the same computational program. A separate thermistor for each computer provided information on injectate temp. For the standard approach, this thermistor was external to the catheter. It was suspended in air near the bag of injectate solution and away from any external heat source, thereby sampling injectate temp in vivo. With the dual thermistor catheter, temp of the injectate was measured in vivo at the site the injectate entered the right atrium. Cardiac output determination was derived using the following formula:

\[
CO = \frac{V_i \rho_i C_i (T_b - T_i) \times F \times 60}{\rho_b C_b \int_0^\infty \Delta D_b(t) dt}
\]

where \(V_i\) = volume of injectate (ml), \(\rho_i\) = specific gravity of injectate, \(\rho_b\) = specific gravity of blood, \(C_i\) = specific heat of injectate, \(C_b\) = specific heat of blood, \(T_b\) = initial temp of injectate (°C), \(T_i\) = initial temp of blood (°C), \(F\) = empiric correction factor for indicator loss between proximal and distal tip of the catheter (used only for the standard technique), 60 = 60 s/min, and \(\int_0^\infty \Delta D_b(t) dt\) = the time-temperature integral following injection.

A total of fifty patients were entered into the study. These individuals were divided sequentially into three groups representing three different forms of chilled injectate thermodilution output determination. The set-up used is depicted schematically in Figure 1. In the first (Cooled Group 1, \(n = 11\)), the thermistor was taped to a bag of sterile saline that had been chilled overnight at 4°C, and the bag was suspended in a slurry of ice and water for a minimum of 20 min. In the second (Cooled Group 2, \(n = 10\)), the thermistor was suspended in a water/ice slurry for at least 20 min which held five syringes prefilled with sterile saline injectate. In the third (Cooled Group 3, \(n = 27\)), a commercially available set-up (CO-Set, Baxter Healthcare Corp., Irvine, California) was used. With this system, the injectate bag was also cooled overnight to 4°C. In contrast to the first group, the distal thermistor was positioned in the outflow tract of the injectate syringe to allow measurement of injectate temp closer to the point of entry into the catheter.

Protocol. All patients were brought to the laboratory in a fasting state. No sedatives or other medications were used routinely. The right heart catheter was inserted through a 7 Fr. sheath placed in the right or left femoral vein. Intracardiac and pulmonary artery pressures were measured during catheter advancement. Injections for CO were performed with normal saline using a thermally insulated syringe with a set capacity of 10 ml (Baxter Healthcare Corp., Irvine, California). In order to approximate common clinical usage more closely, the timing of injections was made without reference to the phase of the respiratory cycle. Sequential injections were separated by a minimum of 20 s to minimize the artifactual effects of recirculation and catheter cooling (13). With the first few patients, chart recordings were made from the distal thermistor signal.
during each injection to verify the proper shape of the resultant time/temp curve.

After measuring blood oxygen content and initiating a 5-min expired gas collection for Fick output measurement, a total of five thermodilution output measurements were made using cooled injectate. The injectate bag and tubing were then switched to ambient temp injectate, and the measurements repeated five times. Finally, the paired arterial and mixed venous blood oxygen measurements and expired gas collection were repeated.

**Fick CO.** Fick CO was measured using standard techniques (17). With the patient breathing ambient air, and after a short period to allow the patient to adjust to the presence of the mouthpiece, the patient's expired gas was collected in a Douglas bag for exactly 5 min. Bag volume was corrected for ambient temp and pressure, and an aliquot was sampled for oxygen content. Paired samples were obtained for determination of blood oxygen content, drawn simultaneously from the pulmonary and femoral arteries.

Differences exceeding 2% mandated repeat sampling until similar paired values were obtained. Oxygen content was computed as the product of blood oxygen saturation times the hemoglobin concentration minus the concentration of both carboxyhemoglobin and methemoglobin. A correction was also used, based on the partial pressure of oxygen, to account for the small fraction of oxygen in blood unbound to hemoglobin. Fick output measurement was performed twice (at the initiation and at the end of thermodilution measurement) with the mean used for comparison against thermodilution outputs.

**Data analysis.** Data are reported as mean ± SD. The chi-square was used to assess differences in dichotomous variables and the two-tailed Student t test differences in continuous variables. Intraclass correlation was used to assess the extent observed measurement variability originated from differences inherent to the two thermodilution measurement techniques (18). A concordance index was also developed to measure the strength of agreement be-
tween the two thermodilution techniques. Each injection was scored as 1 if the simultaneous thermodilution measurements were either both greater than or both less than their respective means and as 0 if one was greater than and one was less than the mean. The overall average score was then normalized to a range of $\frac{2}{1}$ to $\frac{1}{1}$, so that a mean score of 0 would be expected if the two measurement techniques showed no concordance and a mean score of 1.0 expected if complete concordance were present. A p level of 0.05 was accepted as indicating statistical significance.

**RESULTS**

**Baseline patient characteristics.** The clinical and hemodynamic characteristics of the study population are shown in Table 1. For each of the 48 patients, five measurements were performed using ambient temp injectate and five using cooled injectate (total of 960 measurements derived from 480 injections). Thermodilution CO values averaged 5.02 L/min and ranged from 1.27 to 16.44 L/min. A total of 122 of the 960 measurements (12.7%) had values that reflected a substantially low output ($\leq 3.5$ L/min).

**Precision.** The reproducibility of measurement was assessed using sequential injections made while the patient remained hemodynamically stable. As shown in Table 2, when using ambient temp injectate, the dual thermistor technique demonstrated significantly less measurement variability than the standard technique (precision = 0.41 vs. 0.55 L/min, p < 0.001). Similarly, the average range of CO values obtained during the five sequential injections in each patient was less using the dual thermistor approach (1.05 vs. 1.55 L/min, p < 0.001).

Measurements using cooled injectate were more precise than those using ambient temp injectate by both techniques (Table 2). Again, the dual thermistor technique outperformed the standard technique (precision = 0.35 vs. 0.43 L/min, p = 0.01). The lower precision with the standard method was most evident in the Cooled Group 1 (precision = 0.74 L/min), where the bag of injectate was cooled in an ice bath and the temp measured at the bag's surface.

These observed differences in precision provided the theoretic basis for more clinically useful comparisons. For example, thermodilution CO determinations in clinical practice generally employ multiple repeat injections with the average value reported (19). As with any test, extreme individual values can be encountered. For thermodilution output determination, a simple method that could reduce the frequency of these outliers would be helpful. Based on the current study, the likelihood that any single measurement deviates more than 10% from the mean was 29.4% for the dual thermistor approach and 33.6% for the standard technique.

### Table 1. Characteristics of Study Population

<table>
<thead>
<tr>
<th>Clinical Variables</th>
<th>Hemodynamic Variables</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age (yrs) 61 ± 10</td>
<td>heart rate (min$^{-1}$) 70 ± 14</td>
</tr>
<tr>
<td>Gender (% male) 48 (100)</td>
<td>aortic systolic pressure (mm Hg) 127 ± 25</td>
</tr>
<tr>
<td>Weight (lbs) 188 ± 37</td>
<td>PA systolic pressure (mm Hg) 34 ± 16</td>
</tr>
<tr>
<td>BSA (M$^2$) 2.01 ± 0.18</td>
<td>PA wedge pressure (mm Hg) 15 ± 9</td>
</tr>
<tr>
<td>No. with clinical CHF 5 (10)</td>
<td>systemic vasc. resistance (dynes*cm$^{-5}$) 1534 ± 405</td>
</tr>
<tr>
<td>No. with prior MI 17 (35)</td>
<td>cardiac index (L/min/M$^2$) 2.4 ± 0.6</td>
</tr>
<tr>
<td>No. with hypertension 29 (60)</td>
<td>ejection fraction (%) 54 ± 19</td>
</tr>
<tr>
<td>No. with CAD 37 (77)</td>
<td>hemoglobin (g/dl) 13.4 ± 1.8</td>
</tr>
<tr>
<td>No. with low cardiac index 26 (54)</td>
<td>oxygen consumption index (L/min/M$^2$) 131 ± 26</td>
</tr>
<tr>
<td>No. with mitral regurgitation 3 (6)</td>
<td>PA oxygen saturation (%) 61 ± 14</td>
</tr>
<tr>
<td>No. with aortic regurgitation 3 (6)</td>
<td>aortic oxygen saturation (%) 94 ± 3</td>
</tr>
</tbody>
</table>

BSA = body surface area; CAD = coronary artery disease; PA = pulmonary artery; Plus-minus values represent mean ± standard deviation; values in parentheses represent percentages.

### Table 2. Measurement Precision

<table>
<thead>
<tr>
<th>Injectate</th>
<th>Dual Thermistor</th>
<th>Standard</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>SD (L/min)</td>
<td>Mean (L/min)</td>
</tr>
<tr>
<td>Ambient temperature</td>
<td>0.41</td>
<td>4.78</td>
</tr>
<tr>
<td>Cooled combined</td>
<td>0.35</td>
<td>4.77</td>
</tr>
<tr>
<td>Cooled Group 1</td>
<td>0.49</td>
<td>5.16</td>
</tr>
<tr>
<td>Cooled Group 2</td>
<td>0.31</td>
<td>4.62</td>
</tr>
<tr>
<td>Cooled Group 3</td>
<td>0.31</td>
<td>4.68</td>
</tr>
</tbody>
</table>

Significance (p) values refer to the difference in SD between the dual thermistor and standard technique. SD = standard deviation, used as a measure of precision; C of V = coefficient of variation.
approach using ambient temp injections. Comparable values for iced injectate were 18.0% and 22.0%, respectively. The most common downside of repeated measurements is the additional time they take to perform. The improved precision of the dual thermistor approach might theoretically permit the use a smaller number of injections to achieve the same level of accuracy. Figure 2 further explores this possibility. Assuming that averaging five injections provides a reasonable estimate of true CO, the mean anticipated “error” by reliance on a smaller number of injections can be predicted using this graph. As an example, if a mean error of ≤10% was deemed acceptable in a specific circumstance, this analysis estimates that using the standard technique two injections would be required to achieve this result, whereas one injection would suffice if the dual thermistor technique were substituted.

**Intraclass correlation and concordance.** In this study thermodilution CO measurements were made simultaneously by both techniques during every injection. This approach was designed to remove many potential sources of “interinjection” variability that could bias or obscure the results. This approach also provided a unique opportunity to explore to what extent the observed measurement variability originated from differences inherent to the two techniques under study, in contrast to variables the techniques have in common. Figure 3 graphically depicts the differences in measurement for each of the 480 injections. Intraclass correlation was used to help quantitate this effect. This statistic can be used to assess agreement between tests that provide results as continuous measures, in a manner somewhat analogous to the use of the kappa statistic to assess agreement between tests employing interval measures. The intraclass correlation coefficient for the paired measurements for ambient temp injections was 0.91 and for cooled...
injections 0.62. Hence, for ambient temp injections 87% of the measurement variance could be accounted for by factors common to each injection (such as variability in injectate volume, timing differences during injection, etc.). For cooled injections, 60% of the variance could be explained by these variables in common. The remaining variance likely arose from true differences between the two techniques under study.

We also developed a concordance index to represent the frequency at which the two simultaneous measurements both fall above or below the mean of each patient. A value of zero suggests the two measurements are completely independent, indicating no concordance, and a value of one that the two measurements always fall on the same side (either above or below) the mean, indicating complete concordance. The values obtained from analysis of the data were 0.478 for ambient temp injections and 0.582 for cooled injections. These analyses lend further support to the concept that observed measurement variability in this study can be partially accounted for by factors unique to each individual injection but that a substantial amount of the observed variance still depends on inherent differences between the two techniques under study.

An additional index of test performance, incorporating features of both accuracy and precision, was also used that is more directly applicable to the individual patient. The absolute value of the difference between each individual thermodilution and Fick measurement was computed, with the average of these reported as mean error. As shown in Table 3, mean error was significantly less using the dual thermistor technique for both ambient temp (p = 0.019) and cooled (p < 0.001) injectate.

For the 240 pairs of measurements using cooled injectate, the dual thermistor approach more closely approximated Fick CO in 158 (66%), while in 82 (34%) the standard approach was closer to Fick. Therefore, for two out of every three injections the dual thermistor method was more “accurate” relative to the Fick output.

Injectate warming. The set-up used in this study included two thermistors that provided continuous measurement of injectate temperature during each injection. One was positioned external to the catheter and one in the right atrium.

<table>
<thead>
<tr>
<th>Injectate</th>
<th>No. of Meas.</th>
<th>Fick CO (L/min)</th>
<th>Dual CO (L/min)</th>
<th>Mean Difference (L/min)</th>
<th>Mean Error (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ambient temp</td>
<td>480</td>
<td>4.85</td>
<td>4.78</td>
<td>5.17</td>
<td>18.2</td>
</tr>
<tr>
<td>Cooled Combined</td>
<td>480</td>
<td>4.86</td>
<td>4.77</td>
<td>5.35</td>
<td>16.2</td>
</tr>
<tr>
<td>Cooled Group 1</td>
<td>110</td>
<td>4.87</td>
<td>5.16</td>
<td>7.14</td>
<td>15.2</td>
</tr>
<tr>
<td>Cooled Group 2</td>
<td>100</td>
<td>4.97</td>
<td>4.62</td>
<td>4.68</td>
<td>20.1</td>
</tr>
<tr>
<td>Cooled Group 3</td>
<td>270</td>
<td>4.81</td>
<td>4.68</td>
<td>4.87</td>
<td>15.0</td>
</tr>
</tbody>
</table>

The significance (p) values for mean difference compare thermodilution and Fick outputs for each technique while the significance values for mean error reflect the difference between the two thermodilution techniques.

**Table 3. Measurement Accuracy**

CO = cardiac output; dual = dual thermistor catheter technique.

**Accuracy.** Assessment of true accuracy requires the use of a completely reliable CO measurement technique, something that cannot be accomplished in humans. Instead, we have chosen the well established technique of Fick oxygen consumption CO measurement as a reference, with relative agreement of these two measurements serving as a surrogate of thermodilution output accuracy. Overall, as shown in Table 3, ambient temp thermodilution measurements by the dual thermistor technique were statistically similar (−0.08 L/min, p = 0.34) to Fick measurement. In contrast, using the standard technique, ambient temp thermodilution measurements overestimated Fick CO by a mean of 0.32 L/min, a highly significant difference (p = 0.001). This pattern was also observed for the combined cooled injections with the substantial overestimation by the standard technique (0.50 L/min, p < 0.001) not seen with the dual thermistor technique (−0.08 L/min, p = 0.16).

**Figure 4.** Histogram depicting the distribution of warming of the injectate as it traveled down the length of the tubing and thermodilution catheter to the injection port positioned in the right atrium. Only the 240 ambient temperature injections are shown on this graph.
permits analysis of the magnitude of injectate warming as it traveled throughout the reservoirs, tubing and thermodilution catheter. Figure 4 reveals the distribution in temp changes observed during the 240 ambient temp injections, which averaged 2.8°C. Despite a relatively uniform core body temp (36.9 ± 0.8°C) and initial injectate temp (21.5 ± 1.5°C) over all 48 patients, the injectate temp change from measurement site to right atrial injection site varied considerably from injection to injection (2 SD range = −0.22 to 5.74°C). This relationship could also be examined on a per-patient basis. Despite a constant ambient injectate temp and injection pattern in a given patient, the range (highest minus lowest) of actual temps measured at the right atrial injection site for the five sequential injections averaged 0.8°C with values up to 4.4°C noted in some patients. This seemingly small mean difference nevertheless would, by itself, account for an average of 6.3% difference within a series of five sequential thermodilution CO measurements. This potential error was eliminated by the dual thermistor system.

As shown in Figure 5, when cooled injectate was used, this variability in injectate temp change from measurement site to injection site increased further (2 SD range = −4.07 to 8.13°C) based largely on differences in the procedure used to deliver and measure the injectate (mean temp change = 15.6 ± 2.1, 8.9 ± 1.3 and 2.9 ± 1.9°C for Cooled Groups 1, 2 and 3, respectively, p < 0.001). However, even with the technique and the individual patient variables held constant, the range of the five sequential measurements also increased (mean 3.64°C, maximum 9.73°C) when compared with ambient temp injections. Again, this source of variability was avoided completely with the dual thermistor system.

**DISCUSSION**

**Impact on accuracy and precision.** This study demonstrated a significant difference in performance between the standard method of thermodilution measurement now in clinical use, and a novel catheter that incorporates the sensor for injectate temp within the thermodilution catheter itself. Overall accuracy (relative to Fick CO) and mean error were significantly improved with the dual thermistor catheter system. This improvement was observed both when the indicator solution was used at ambient temp and when cooled to near 0°C, although most of the inaccuracies associated with cooled injections occurred with Cooled Group 1.

Precision provides a related but different measure of test performance. It is more important than accuracy when changes in CO are considered the primary issue, as might occur during titration of hemodynamically active medications. Precision is also closely related to the common practice of averaging several sequential measurements to obtain a single, and presumably more reliable, value for CO. A more precise technique would require a smaller number of repeat measurements to achieve the same level of reliability. Overall, our data revealed a significant improvement in precision using both ambient temp (p < 0.001) and cooled (p = 0.01) injectate. When the three subgroups of cooled injectate were considered separately though, two showed no statistically significant difference between the dual thermistor and standard techniques.

**Implications of injectate warming.** Overall, the standard thermodilution technique, using either ambient temp or cooled injectate, significantly overestimated Fick CO (p ≤ 0.001) whereas the dual thermistor catheter system did not statistically differ from Fick output. A logical explanation for this disparity lies in the location used for assessment of injectate temp (12, 20). Measurement ex vivo ignores the temp change (“loss of indicator”) that occurs as the fluid traverses the tubing, injection syringe, and/or the thermodilution catheter caused by both external warming and internal friction. Manufacturers have attempted to compensate for this error by automatic or manual entry of an empirically derived “correction factor” (2). Our data, though, suggest that this correction factor, which was developed and tested in vitro, is inadequate in predicting temp changes occurring during clinical use in humans. After applying this correction factor, the magnitude of the remaining underestimation, averaging 1.38°C for ambient temp injectate and 1.62°C for cooled injectate, would result in a falsely elevated CO in the range of 6% to 11%. This is approximately the range of overestimation observed in this study.

Even if a more appropriate correction algorithm were devised, significant inaccuracy with the standard thermodilution system could still be anticipated for two reasons. First, as shown in Figure 4, even under well-controlled circumstances the variability of measured temp change...
during injectate transit measured in vivo was both substantial and unpredictable. The approximately 8°C range encountered could theoretically lead to output readings differing by as much as 89%. Second, even given a set injectate temp, volume and composition, our data show that the extent of injectate warming is highly dependent on the exact set-up used. For example, although the initial injectate temp in our three subgroups was comparable, measuring injectate temp at the surface of the chilled injectate bag resulted in a mean warming of 15.6°C, use of chilled syringes a mean warming of 8.9°C and measuring temp close to the catheter hub a mean warming of 2.9°C.

Choice of injectate temp and thermistor position.
Cooled injectate has the theoretic advantage of increased accuracy due to a larger temp gradient between indicator and blood. Because of this improved signal-to-noise ratio, injections with cooled solution are widely advocated in the literature (5,21). Surprisingly, using the standard technique, this potential advantage was not borne out. Irrespective of the method selected for assessing injectate temp (bag in ice bath vs. cooled syringe vs. CO-Set), the mean error was greater for cooled than for ambient temp injections. This is likely because any theoretic advantage of this approach is more than offset by practical problems in measuring true injectate temp as it enters the right atrium. Additionally, the mean overestimation of Fick output observed with the standard technique with ambient temp injections (0.32 L/min) further increased with cooled injections (0.50 L/min). This finding could also be anticipated as thermal “contamination” between the point of measurement, and the point of injection would have a more profound effect on cooled injectate. Neither of these problems were observed with the dual thermistor catheter. Hence, although the use of cooled injections for thermodilution output improves accuracy with the dual thermistor catheter, it actually appears to degrade the accuracy of the conventional thermodilution catheter.

Three different arrangements for cooled injections were used in this study (Fig. 1). A cautious interpretation of subgroup comparisons is warranted given the smaller number of patients in each subgroup. Nevertheless, it is clear that the approach used in Cooled Group 1 (injectate bag in ice slurry with the thermistor strapped to the bag) provides the poorest results. This method overestimated Fick CO on average by more than 2 L/min, while also posting the worst precision (0.74 L/min).

Potential limitations. In evaluating these results it is important to bear in mind several potential limitations of the study. First, the range of COs observed in this population included few extremely low values that might be encountered with cardiogenic shock or other low output states. Extrapolation of our results to patients such as these should be done with caution. Second, injections were not timed to coincide with end-expiration, as advocated by some (22,23). We purposely chose to ignore the respiratory stage during measurement to more closely mimic clinical practice in this region. Although we would anticipate that limiting injections to end-expiration would slightly improve the precision observed, we would not expect any changes in the relative differences encountered between the two catheter systems. Moreover, we would not anticipate improved accuracy relative to Fick, as this other technique obviously measures CO averaged over the entire respiratory cycle. Third, we used the closeness of agreement to Fick output as a surrogate of thermodilution accuracy. Although the Fick technique clearly possesses its own inherent variability and error, use of an extremely accurate standard for comparison is impossible in human investigation. Fourth, our thermodilution measurements were done with careful attention to detail, such as avoidance of hand warming of the injectate syringe contents before injection. In routine clinical practice these nuances might not be as carefully observed. The anticipated net result would be a degradation of precision and accuracy, particularly with the standard technique, which would further increase the differences found with the dual thermistor and the standard approaches.

Clinical implications. Due to the widespread use of thermodilution catheters in multiple settings such as the intensive care unit, operating suite and catheterization laboratory, modest improvements in the technique could still have a major impact in clinical care. In comparing the two thermodilution techniques, only 16 of 480 (3.3%) simultaneous measurements differed by more than 1.0 L/min. However, more moderate discrepancies were relatively common, as 82 of 480 (17.1%) simultaneous measurements differed by at least 0.5 L/min. With both ambient temp and cooled injections, use of the dual thermistor technique resulted in a limited but clinically and statistically significant improvement in overall precision and accuracy. The dual thermistor catheter system offers other important advantages as well, such as a much shorter set-up time, avoidance of a mandatory ice bath for cooled injections, autosensing of injections that obviates manual triggering of the CO computer and visual feedback of bolus integrity via a visual display of the injectate thermistor signal. The use of a dual thermistor thermodilution catheter system should be strongly considered for all applications where a reliable estimate of CO is desired.

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