Simultaneous Intraoperative Measurement of Cardiac Output by Thermodilution and Transtracheal Doppler

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Intraoperative measurement of cardiac output with transtracheal Doppler (DOP) was compared with that measured by thermodilution (TD). Cardiac output was measured simultaneously with both methods in 17 adult patients. For 86 pairs of measurements, the average difference between the two techniques was −0.2 l·min⁻¹. This bias had a standard deviation of 1.7 l·min⁻¹. The average of the absolute value of the difference between measurements made with the two techniques was 1.3 l·min⁻¹, with a standard deviation of 1.1 l·min⁻¹. The limits of agreement were −3.6 to 3.1 l·min⁻¹. Linear regression yielded the following equation: DOP = 0.62 TD + 1.54 l·min⁻¹ (r = 0.68). To evaluate the ability of transtracheal Doppler to trend changes in cardiac output, the changes in cardiac output at sequential time points were compared for the two techniques. The average difference in the changes in cardiac output measured by the two techniques was 0.0 l·min⁻¹. This bias had a standard deviation of 1.7 l·min⁻¹. In conclusion, the transtracheal Doppler technique did not reproduce the measurement of cardiac output by TD intraoperatively. Transtracheal Doppler did not accurately trend changes in the TD measurement. These findings were obtained from patients with cardiovascular disease, and the conclusions may depend in part on the patient population and the investigators' experience with the transtracheal Doppler technique. (Key words: Heart; cardiac output. Measurement technique: cardiac output; Doppler; noninvasive; transtracheal.)

Continuous noninvasive measurement of cardiac output would be useful for hemodynamic monitoring of patients. Recently, a technique was introduced to measure cardiac output in patients whose tracheas are intubated.1–3 This method uses a 5-mm, 5-MHz pulsed Doppler (DOP) ultrasound transducer mounted on the tip of a standard endotracheal tube to obtain the aortic diameter and the Doppler shift of the ultrasound beam reflected by blood in the ascending aorta proximal to the major aortic arch vessels. From these data, cardiac output is calculated every 12 s and displayed.

Linear regression statistical analysis has been used in previous studies in dogs4 and humans,1,5 and good correlation has been shown between measurements of cardiac output with transtracheal Doppler and thermodilution (TD) for a small number of measurements. There have been no studies comparing a large number of simultaneous measurements of cardiac output by transtracheal Doppler and TD. Also, the ability of transtracheal Doppler to accurately measure changes in cardiac output over time has not been demonstrated. This study compares the measurement of cardiac output by transtracheal Doppler with that by TD in anesthetized patients during major cardiovascular operations.

Materials and Methods

With approval of the Stanford University Institutional Review Board on the Use of Humans in Research and individual informed consent, 19 patients older than 21 years of age undergoing elective major cardiovascular surgery were studied. Only patients who required insertion of a pulmonary artery catheter as deemed necessary by their attending anesthesiologist were included. Patients scheduled for cardiac surgery were evaluated by cardiac catheterization and two-dimensional echocardiography. Patients were excluded if there were abnormalities or previous surgery involving the aortic arch, or if they required intraaortic balloon counterpulsation.

A pulmonary artery catheter was inserted before the induction of anesthesia. After induction, an investigator intubated the patient's trachea with the Doppler Tube® (8 or 9 mm internal diameter; Applied Biometrics, Minnetonka, MN) in the usual manner. An audio representation of Doppler flow signals and a visual representation of forward and reverse flow were used by the investigator for optimal tracheal tube positioning.5 The audio signal was considered suboptimal if it contained a preponderance of low-frequency thumping sounds instead of higher-frequency whistling sounds. The thumping sounds were taken to be suggestive of aortic wall motion, and thus indicative that the velocity was not being measured from the center of the lumen of the aorta. The visual display showed the amplitude of forward and reverse flow and was considered inadequate if the forward-flow signal was less than four times the reverse-flow signal. The audio and visual indicators were also used to determine when mechanical ventilation interfered with acoustic contact of the ultrasound probe against the wall of the trachea. The signals were considered suboptimal if the amplitude was reduced by 50% or more as a cyclic function of respiration. All decisions regarding the adequacy of the DOP signal were made by an investigator who was totally unaware of any of the TD measurements. The elapsed time to obtain

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an adequate cardiac output signal from the tracheal Doppler after intubation was measured. If an adequate cardiac output signal was unobtainable, the patient was excluded from the study. Breath sounds were auscultated after positioning of the Doppler Tube® to assure there was not an endobronchial intubation.

Measurements of cardiac output were obtained in triplicate with the use of a TD pulmonary artery catheter (93A-131H-7F; American Edwards Laboratory, Santa Ana, CA) and a TD cardiac output computer (series 7010RA; Marquette Electronics, Milwaukee, WI) with a 10-ml saline injectate at room temperature at end-expiration. An average of the three measurements was calculated. Any cardiac output significantly aberrant (greater than ±10%) from the other two was excluded, and a repeat measurement was obtained. Concurrent measurements from the tracheal Doppler and ABCOM® (V2.80; Applied Biometrics) cardiac output computer were recorded by a second investigator blinded to the TD results. Data were not collected during electrocautery. Data were also excluded if the amplitude of forward flow on the Doppler visual display was inadequate or if the audio representation of the Doppler signal was suboptimal. The adequacy of the Doppler signal was determined without any information about TD measurements. The display of the Doppler cardiac output measurement was updated every 12 s. All of the displayed values were recorded during the time interval in which the TD measurements were obtained. The Doppler cardiac output measurements were averaged to obtain the average value for the time interval. Cardiac output was measured at specific moments when possible; it was measured after intubation, after incision, and any time there was a 25% change in pulse or blood pressure or any other clinical indication. In patients undergoing cardiopulmonary bypass, measurements were obtained after sternotomy, during aortic and atrial dissection and cannulations, and after cardiopulmonary bypass.

Data were analyzed by first plotting cardiac output by TD versus cardiac output by tracheal Doppler and obtaining an equation of linear regression. Because linear regression analysis establishes a linear relation between two measurements but does not establish agreement between two values, we further analyzed the data with the method of Bland and Altman. The difference between two measurements is the error, and the average error is the bias. Thus, the bias is the offset that could possibly be subtracted from the measured variable to yield better agreement with the standard. We also determined the mean of the absolute value of the error. This result is the magnitude of the average disagreement between the two methods. The performance of a clinical measuring device may depend on the experience of the operator. Each investigator had previously used the TD technique more than 500 times. Training with the tracheal Doppler technique included instructions and demonstration by the manufacturer and use of the instrument in eight patients before this study began. To examine the hypothesis that additional experience would improve the performance of the tracheal technique, the bias and the variance of the error were calculated for each patient. Homogeneity of variance was examined with Bartlett's test, and the Spearman rank correlation was calculated to determine the presence of a trend in the bias, absolute bias, or variance as a function of the patient number. To determine the ability of tracheal Doppler to measure changes in TD cardiac output, we considered changes in cardiac output in sequential tracheal Doppler measurements as a function of corresponding TD measurements. To evaluate the possibility that the patient's position for cardiac surgery interfered with the function of the Doppler Tube®, the data from the noncardiac surgery patients were analyzed as a subgroup. The bias for these two groups was compared with a two-tailed t test.

Results

Of the 19 patients enrolled in the study, data were obtained from 17 patients to yield 86 measurements of cardiac output. In 1 patient, an adequate Doppler signal could not be obtained. Another patient became hemodynamically unstable on induction of anesthesia, and the study was terminated to avoid interference with patient care. There were periods of time during which data were not collected because the Doppler signal was inadequate in 8 patients. Table 1 lists the types of cases included in the study. The average time to position the Doppler Tube® to obtain an adequate signal was 10 ± 5 min (mean ± SD). There were no incidents of endobronchial intubation after the tracheal tube was positioned. The range of tracheal Doppler cardiac output measurements was 1.1–9.7 l·min⁻¹. Figure 1 shows cardiac output measured by TD versus cardiac output by tracheal Doppler for each measurement. This plot yielded an equation of linear regression: Doppler = 0.62 TD + 1.54 l·min⁻¹ with a Pearson product-moment correlation coefficient of r = 0.65. Figure 2 shows the difference between TD and Doppler measurements (i.e., the error) versus the average measurement for the two methods. We chose to average the values from TD and Doppler to minimize any inaccuracies on the assumption that TD does not represent a true "gold standard" method of measuring cardiac output. As shown in figure 2, the bias was −0.21 l·min⁻¹, with a standard

**Table 1.**

<table>
<thead>
<tr>
<th>Patient</th>
<th>Surgical Procedure</th>
<th>Age (yr)</th>
<th>Sex</th>
</tr>
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<tr>
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<td>AVR</td>
<td>52</td>
<td>F</td>
</tr>
<tr>
<td>2</td>
<td>CABG</td>
<td>67</td>
<td>F</td>
</tr>
<tr>
<td>3</td>
<td>MVR/CABG</td>
<td>63</td>
<td>M</td>
</tr>
<tr>
<td>4</td>
<td>CABG</td>
<td>62</td>
<td>M</td>
</tr>
<tr>
<td>5</td>
<td>CABG</td>
<td>67</td>
<td>M</td>
</tr>
<tr>
<td>6</td>
<td>Pheochromocytoma</td>
<td>49</td>
<td>M</td>
</tr>
<tr>
<td>7</td>
<td>AVR</td>
<td>50</td>
<td>F</td>
</tr>
<tr>
<td>8</td>
<td>TVR</td>
<td>68</td>
<td>M</td>
</tr>
<tr>
<td>9</td>
<td>Pericardectomy</td>
<td>48</td>
<td>M</td>
</tr>
<tr>
<td>10</td>
<td>CABG</td>
<td>72</td>
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<td>11</td>
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<tr>
<td>12</td>
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<tr>
<td>14</td>
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<tr>
<td>15</td>
<td>CABG</td>
<td>69</td>
<td>M</td>
</tr>
<tr>
<td>16</td>
<td>CEA</td>
<td>61</td>
<td>M</td>
</tr>
<tr>
<td>17</td>
<td>CEA</td>
<td>76</td>
<td>F</td>
</tr>
</tbody>
</table>

AVR = aortic valve replacement; CABG = coronary artery bypass graft; MVR = mitral valve replacement; TVR = tricuspid valve replacement; CEA = carotid endarterectomy.

deviation of $1.7 \pm 1.1 \text{ l/min}^{-1}$, and the absolute error was $1.3 \pm 1.1 \text{ l/min}^{-1}$. Figure 2 suggests that the error did not show any dependence on cardiac output for the range of cardiac output measured. The Pearson product-moment correlation coefficient for the error (DOP-TD) versus the average of the measurements for the two methods $(\frac{1}{2}(\text{DOP} + \text{TD}))$ was $r = 0.04$. Approximately 95% of the errors were within $-3.6$ to $3.1 \text{ l/min}^{-1}$. The bias of $-0.2 \text{ l/min}^{-1}$ has a 95% confidence interval of $-0.5$ to $0.1 \text{ l/min}^{-1}$. This confidence interval depends on the study sample size and shows that, for this size population, the average error was not statistically different from zero. The limits of agreement of $-3.6$ to $3.1 \text{ l/min}^{-1}$ are also dependent on the population size. The 95% confidence interval for the lower limit of $-3.6 \text{ l/min}^{-1}$ is $-4.1$ to $-3.1 \text{ l/min}^{-1}$. The 95% confidence interval for the upper limit of $3.1 \text{ l/min}^{-1}$ is $2.6$ to $3.6 \text{ l/min}^{-1}$. The bias and magnitude of 2 standard deviations are shown in figure 3 for each patient. Bartlett's test for homogeneity of group variances was significant ($P < 0.01$), suggesting that the variances of the errors for individual patients were not homogeneous. The Spearman correlation coefficient ($r_s$) for variance of the error versus patient number was 0.13. For bias versus patient number, $r_s = 0.16$; and for the magnitude of the bias versus patient number, $r_s = 0.49$.

Changes in cardiac output with time are of great clinical interest. The change in cardiac output at sequential time points was calculated for TD and transtracheal DOP. Figure 4 shows the changes in cardiac output observed with transtracheal DOP ($\Delta$DOP) versus the changes in cardiac output observed with TD ($\Delta$TD) for the same time in-

![Figure 1](image1.png)

**Figure 1.** Comparison of cardiac output (CO) measured with transtracheal Doppler (DOP) and thermodilution (TD). Cardiac output was measured simultaneously with transtracheal Doppler and thermodilution in 17 patients. The solid line of identity is shown for reference. Linear regression of the 86 measurements yields the dashed line with equation DOP = 0.62 TD + 1.54, and the Pearson product-moment correlation coefficient is 0.63.

![Figure 2](image2.png)

**Figure 2.** Limits of agreement. The difference between simultaneous measurements of cardiac output with thermodilution (TD) and transtracheal Doppler (DOP) is plotted against the mean of the two techniques for 86 measurements in 17 patients. The mean difference was $-0.2 \text{ l/min}$ and is designated with a horizontal line. The standard deviation (SD) was $1.7 \text{ l/min}$. Lines designating the mean difference $\pm 2$ SD are shown to indicate the limits of agreement.
Fig. 3. For each patient, the bias and the magnitude of two standard deviations (SD) for the difference between the transtracheal Doppler measurement (DOP) and the thermodilution measurements (TD) are shown. The limits of agreement for each patient can be taken as bias ± 2 SD. There were significant differences in the variances between patients (Barlett's test, P < 0.01). The patient number corresponds to the order in which they were studied. No improvement in the bias or variance as the study progressed could be demonstrated.

Fig. 4. Change in cardiac output over time. The change in cardiac output at sequential time points is plotted for the two measurement techniques. The line of identity is shown as a solid line. Points that do not lie on this line represent time intervals over which the transtracheal measurement and the thermodilution measurements changed by different amounts. Linear regression of the 69 measurements yields the dashed line with equation \( \Delta \text{DOP} = 0.43 \Delta \text{TD} + 0.10 \), and the Pearson product-moment correlation coefficient is 0.42.

Discussion

In this patient population, measurements of cardiac output with transtracheal DOP were not in agreement with TD measurements. A value of 1.3 l min\(^{-1}\) for the absolute error shows that, on average, the DOP measurement differed from TD by 1.3 l min\(^{-1}\) for a given instance. The 95% confidence interval on the bias included zero; thus, in this study we were unable to add an offset to the DOP measurements to yield better agreement. Transtracheal DOP did not accurately relate changes in TD cardiac output, as shown by the great deal of scatter around the line of identity in figure 4. Although there are limitations to measuring cardiac output by TD, it is a clinically accepted and useful technique. Some possible causes for the discrepancies between transtracheal DOP and TD are user skill, study population, and assumptions inherent to the transtracheal DOP technique.
Each of the investigators was instructed by the manufacturer in Doppler Tube® positioning and practiced on several patients before beginning this study. There appears to be some learning involved in correctly positioning the Doppler Tube®, and our results may have improved over time if the study had been continued. If experience with the transthoracic technique had led to improved results, we would have expected the bias, absolute bias, and variance of the difference between the transthoracic Doppler and TD measurements to have trended toward zero as the study progressed. No such trend could be demonstrated; thus, we were unable to show significant improvements over the course of studying 17 patients.

The results of this study may have been affected by the selection of the patient population. Most of the patients underwent cardiac operations. Many of these patients have aortic disease that may affect the Doppler measurement. Surgery requiring manipulation of the aorta might disturb the blood velocity profile in the aorta. Such changes would be expected to have a greater impact on Doppler measurements than on TD measurements. In addition, the Hyperextended sternotomy position, in which the patient is placed for cardiac operations, may make positioning of the Doppler Tube® more difficult. When the study population was divided on the basis of the type of surgery, the error was of greater magnitude in the non–cardiac surgery group. Cardiac output in the non–cardiac surgery group was underestimated by Doppler more than it was in the cardiac surgery group. This result is consistent with the observation that the Doppler technique tended to underestimate high cardiac output conditions. The average TD cardiac output in the non–cardiac surgery group was 7.0 l·min⁻¹, but it was only 4.0 l·min⁻¹ in the cardiac surgery group. However, better results were not obtained in the patients that did not undergo cardiac operations. This group contains only three patients and does not constitute a controlled comparison group. A much larger study would be needed to define subpopulations for which the performance of the transthoracic Doppler technique might vary. Performance was poor in this study even when the non–cardiac surgery patients were excluded from the analysis.

The transthoracic technique makes multiple assumptions, which may each contribute to the overall error. The angle between the Doppler signal and the direction of blood flow is used to calculate both the aortic diameter and the blood velocity. This angle was previously determined by measuring aortic diameters transcutaneously in 18 patients with B-mode echocardiography and finding the angle that minimized the sum of the squares difference between the transcutaneous aortic diameter and the transthoracic diameter. The angle (52.4 degrees ± 3.8 degrees) is considered a constant for all patients and is used in the cardiac output computer (ABCOM 1®, V2.80) to determine aortic diameter and blood velocity. Based on this assumption of constant angle, an error of 14% in cardiac output measurement is introduced when a patient is studied. The transthoracic Doppler technique also assumes the aortic diameter is constant throughout the cardiac cycle. It has not been studied whether the increase in aortic diameter with systole is enough to contribute significant error. Finally, there is probable error in the assumption that the velocity profile across the aortic diameter is constant.

The ABCOM 1® averages cardiac output over a 12-s interval, thereby averaging any changes in cardiac output with ventilation. In patients whose lungs are mechanically ventilated, the cardiac output measured with TD at end-expiration may be different from the average cardiac output throughout the ventilatory cycle. All of the TD measurements were obtained at end-expiration, and this timing may have added to the discrepancies in measurements. By averaging three cardiac output measurements obtained at end-expiration, the variability was reduced. The variability of the transthoracic technique is low because the 12-s averaging intervals permit data from more than ten heart beats to be averaged to yield the reported measurement. Although respiratory timing of the TD measurements might introduce a bias when compared with the transthoracic Doppler method, the wide range of variances seen across patients is probably not related to the respiratory timing. We were unable to relate the variability of the TD measurements to the magnitude of the difference between the TD and the transthoracic Doppler methods.

Previous studies comparing transthoracic Doppler with TD showed better correlation between the two methods. A study of seven adult patients yielding 18 measurements gave a correlation coefficient of 0.93. Another study of eight patients and 38 measurements determined a correlation coefficient of 0.91. The range of cardiac output measured by the first study was 4–8.5 l·min⁻¹ and the second, 2.5–10 l·min⁻¹. Both investigations report only linear regression in the statistical analysis. Neither study specified patient population nor the criteria for inclusion or exclusion of data. In contrast to the current study, the tracheal measurement technique in these studies may have been affected because the investigator had knowledge of simultaneous TD measurements. Discrepancy with the current study may result from these differences.

In conclusion, in this patient population transthoracic Doppler did not accurately predict cardiac output or changes in cardiac output as measured by TD. Future development of the transthoracic Doppler technique should consider analysis of inaccuracies introduced by the assumptions used in the current design. Additional investigation and development will elucidate the role of transthoracic Doppler in the practice of anesthesiology.
References


