Determination of Cardiac Output in Critically Ill Patients by Dual Beam Doppler Echocardiography

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Recent technology in Doppler echocardiography has produced a dual beam Doppler instrument that is capable of insonating the total cross-sectional area of the ascending aorta. The purpose of this study was to evaluate the accuracy of this instrument in measuring cardiac output in critically ill patients by comparing results with those of the thermodilution-derived cardiac output. A technically adequate Doppler cardiac output measurement was attained in 71 (91%) of 78 patients. The range of thermodilution-derived cardiac output measurements was from 1.58 to 11.70 liters/min.

To maximize thermodilution cardiac output reliability, several measurements were made for each patient. Those patients in whom the difference between the highest and lowest measurement varied by <10% from the averaged results were accepted into the 50 patient study. There was significant correlation between dual beam Doppler- and thermodilution-derived cardiac output (r = 0.96, SEE = 0.55 liters/min, p < 0.0001). This study demonstrates that dual beam Doppler ultrasound is a promising noninvasive method of measuring cardiac output in the critically ill patient.

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Measurement of the cardiac output is very useful in many clinical situations. Clinically acceptable methods for accurately measuring cardiac output involve invasive hemodynamic monitoring, which has an associated morbidity and mortality. Since the introduction of Doppler echocardiography and the ability to measure blood flow velocity, there has been increased interest in developing a noninvasive, reliable method for measuring cardiac output. Previous Doppler systems required measurement of the blood flow velocity as well as precise measurement of the aortic diameter. These systems also required the acceptance of certain flow dynamic assumptions.

Recent technology has introduced a dual beam pulsed wave Doppler system that is capable of insonating the total cross-sectional area of the ascending aorta. By directly measuring the aortic cross-sectional area at the same time the flow velocity is measured, this method is independent of the aortic diameter and of the angle of insonation relative to the vector of aortic flow. In this study, we attempted to determine the reliability and accuracy of this dual beam Doppler system in measuring the cardiac output by performing blind comparisons with the thermodilution method of measuring cardiac output.

Methods

Study patients. By protocol our study group consisted of 50 patients with reliable thermodilution cardiac output measurements; these measurements were compared with the Doppler-derived cardiac output. Reliable thermodilution studies were defined as those in which the difference between the highest and lowest individual thermodilution measurement varied by <10% from the averaged value. Patients with aortic valve stenosis, aortic valve regurgitation, an aortic valve prosthesis or recent surgical procedures of the suprasternal notch such as a tracheostomy were excluded from the study. A total of 78 consecutive adult patients with a pulmonary artery thermodilution catheter had a Doppler cardiac output measured. Eight of the 78 patients had technically inadequate Doppler studies as defined by the inability to attain consistent power return and velocity waveforms. Comparative thermodilution studies were not performed on these eight patients. To attain the 50 patient...
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Figure 1. Optimal transducer placement in the suprasternal notch with the two concentric Doppler beams directed on the ascending aorta. A = aortic cross-sectional area; Ap = projected aortic cross-sectional area; θ = angle of insonation relative to direction of aortic flow; V = velocity vector of aortic flow.

The cross-sectional area of the aorta is measured by utilizing the power returns of both beams. The intensity of each Doppler shift frequency is proportional to the number of erythrocytes moving at a specific velocity. The sum of all these intensities (power return) is proportional to the total number of all moving erythrocytes within the cross-sectional area. The power of the wide beam (Pw) is equal to the projected aortic flow lumen area (Ap) x an unknown attenuation constant (Ka). Similarly, the power of the narrow beam (Pn) is equal to the precalibrated known area of the narrow beam (An) x the same unknown attenuation constant (Ka):

\[ P_w = \frac{Ka \times Ap}{P_n} \quad \text{and} \quad Ap = \frac{An \times P_w}{P_n} \]

Because the cross-sectional area is determined by the ratio of power returns of both beams, that area is equal to the calculated area of the wide beam even though the wide beam of insonation overlaps the aortic cross-sectional area. If there exists an angle of insonation relative to the aortic flow vector (Fig. 2), rules of geometry state that the actual cross-sectional area (A) is equal to the projected area (Ap) x the cosine of the angle of incidence:

\[ A = Ap \times \cos \theta. \]

Because \( Ap = \frac{An \times Pw}{Pn} \), then the actual area \( A = \frac{An \times Pw}{Pn} \times \cos \theta. \)

Volume flow (Q) is the product of cross-sectional area and mean velocity:

\[ Q = (An \times Pw/Pn \times \cos \theta) \times \left( \frac{Fd}{\cos \theta} \right) \]

The cosine θ function cancels out of the equation and the measurement becomes angle independent as long as the
cross-sectional area of the aorta is within the wide beam of insonation. The absolute volume flow rate is dependent on a precalibrated attenuation constant $K$, therefore:

$$Q = K \times A_n \times \frac{P_w}{P_n} \times F_d.$$  

**Cardiac output (CO)** is volume flow/min, therefore:

$$CO = K \times A_n \times \frac{P_w}{P_n} \times F_d \times HR.$$  

**Doppler cardiac output measurements.** All dual beam Doppler cardiac output measurements were performed by one investigator (D.S.L.) who was knowledgeable in anatomy but without previous training in echocardiography or Doppler ultrasound. The cardiac output was measured without knowledge of the patient's previous hemodynamic status.

The Doppler transducer was placed in the suprasternal notch position and directed toward the aortic root. Transducer placement was critical for obtaining consistent reliable results. Transducer position was determined by the specific audio signal of aortic flow and then optimized by maximizing the power return of the narrow beam, indicating midposition within the aortic root. Sampling depth was optimized by withdrawing the sample site above the echo interference due to aortic valve motion and by adjusting to the level of maximal flow velocity in the aortic root. An attempt was then made to maximize the number of consecutive beats to be used for calculations. For very ill patients in the intensive care unit, the number of consecutive beats was occasionally limited to two or three, usually because of respiratory distress, inability of the patient to lie still, ventilator interference or an arrhythmia. With the use of an online computer, velocity and power waveforms can be evaluated. Power return waveforms must have maximal amplitude and a peak that is flat or slightly downsloping. Velocity waveforms must be smooth and peaked, and the tracing should have minimal wall motion artifact. If the waveform was consistent with adequate transducer placement, the velocity and power waveforms were then averaged and immediate measurements of cardiac output, heart rate, stroke volume and flow acceleration were attained (Fig. 3). The measurements were repeated for a total of two to five sets of results depending on the number of consecutive beats and the consistency of the waveforms. To maximize Doppler reliability, the transducer was removed and repositioned between all measurements. The values of each measurement were then averaged.

**Thermodilution cardiac output measurements.** Thermodilution cardiac output measurement was performed by well trained medical and surgical intensive care nursing personnel who did not know the results of Doppler cardiac output measurement. Cardiac output temperature curve analyses and computations were performed with a Hewlett-Packard 78552B or an American Edwards Laboratories COM-1 computer. Thermodilution cardiac output was measured within 10 min of the Doppler cardiac output and at a very similar
hemodynamic status. Standard protocol was to use three to five 10 ml injections of a room temperature solution of 5% dextrose in water, attaining the measurements that were in agreement. Outliers were discarded at the discretion of the nurse, and other measurements were taken for a total of three consistent values that were then averaged. To maximize reliability of thermodilution cardiac output measurements, only patients in whom the difference between the highest and the lowest value varied by <10% from the averaged result were included in the 50 patient study.

Table 1. Correlation Coefficients and Standard Error of Estimation (SEE) in the 50 Patient Study, in All Studies and in the Study Comparing the Most Reproducible Measurements of Both Methods

<table>
<thead>
<tr>
<th>No. of</th>
<th>No. of</th>
<th>r</th>
<th>p Value</th>
<th>SEE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patients</td>
<td>Studies</td>
<td></td>
<td></td>
<td>liters/min</td>
</tr>
<tr>
<td>50 patient study</td>
<td>50</td>
<td>0.96</td>
<td>&lt;0.0001</td>
<td>0.55</td>
</tr>
<tr>
<td>CO = &lt;4.00 liters/min</td>
<td>9</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CO = 4.00 to 6.50 liters/min</td>
<td>33</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>CO = &gt;6.50 liters/min</td>
<td>8</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>All studies</td>
<td>71</td>
<td>0.94</td>
<td>&lt;0.0001</td>
<td>0.62</td>
</tr>
<tr>
<td>Both methods with &lt;10% variation</td>
<td>27</td>
<td>0.97</td>
<td>&lt;0.0001</td>
<td>0.54</td>
</tr>
</tbody>
</table>

CO = cardiac output; r = correlation coefficient; SEE = standard error of the estimation.

Results

Adequacy of measurements and reproducibility. Successful dual beam Doppler determinations of cardiac output were obtained in 71 of the 78 consecutive patients, for an overall success rate of 91%. In the 50 patient subgroups, cardiac output ranged from 2.89 to 11.70 liters/min. Overall, measured cardiac output ranged from 1.58 to 11.70 liters/min. The variability of each study was determined and defined as the ratio of the greatest difference between the measurements and the average result. The mean variability in serial dual beam Doppler measurements of cardiac output in the 74 studies was 9.9%. This variability compares with that of 9.3% in the serial thermodilution measurements in the same patients. Variability within 15% of the average Doppler result was attained in 81% of the measurements; in comparison, 85% of the thermodilution measurements agreed within 15% of the averaged result.

Doppler-thermodilution cardiac output correlation. Table 1 lists the correlation coefficients for the comparison between Doppler and thermodilution cardiac output measurements. The 50 patient study revealed a correlation coefficient of 0.96 and a standard error of estimation (SEE) of 0.55 liters/min. The SEE in the low (2.89 to 3.99 liters/min) cardiac output and normal (4.00 to 6.50 liters/min) cardiac output range was 0.48 and 0.45 liters/min, respectively. The SEE tends to increase in the high cardiac output range (6.50 to 11.70 liters/min, SEE 0.88 liters/min) (Fig. 4, upper left). This group of patient studies also showed better correlation in the low and normal cardiac output range (1.58 to 6.50 liters/min) and somewhat lower correlation in the high cardiac output range (6.51 to 11.70 liters/min) (Fig. 4, lower left).

The final analysis compared Doppler and thermodilution cardiac output values in all patients in whom the difference of the highest and lowest value varied by <10% from the averaged result in both methods. In essence we compared the most reproducible studies of each method. The correlation coefficient was 0.97 (SEE 0.54 liters/min) (Fig. 4, upper right).

Discussion

This study demonstrates that cardiac output in the intensive care setting can be measured noninvasively by using a dual beam Doppler system with results that significantly correlate with thermodilution cardiac output measurements. The thermodilution method is far from a perfect reference standard (4,5). In the intensive care unit setting, however, it has been the only reliable method available. To maximize thermodilution reliability, only patients with minimal thermodilution cardiac output variation were accepted into the 50 patient study.

Previous investigators have used Doppler ultrasound and echocardiography to estimate cardiac output. These noninvasive cardiac output measurements have been compared with the invasive Fick, indicator dye and thermal dilution methods of measuring cardiac output (Table 2).

Potential errors of previous studies. Previous efforts (4,6,10,12,17) to measure cardiac output noninvasively required measurements of the aortic diameter with either M mode or two-dimensional echocardiography and measurements of aortic blood velocity by Doppler ultrasound. These methods also required the acceptance of certain assumptions that are not necessary with the dual beam Doppler system.

In previous methods (4,6,10,12,17,18), the aortic cross-sectional area was determined by the equation \((D/2)^2 \pi\), thus...
Figure 4. Linear regression plots of cardiac output values calculated by the dual beam Doppler method versus values obtained by thermodilution in the 50 patient study (A), in all 71 studies (B) and in the 29 patient study comparing the most reproducible measurements of both methods (C). The solid line represents the line of regression and the broken lines represent the 95% confidence interval.

requiring precise diameter (D) measurements. The site of aortic diameter measurement in these studies (6,12-14,18,19) has varied from the level of the left ventricular outflow tract to the level of the ascending aorta 3 cm above the aortic valve. This method of measuring the aortic cross-sectional area also assumes that the aorta is circular throughout the systolic cycle (5,12,13,17). The diameter is measured during systole (6,19) because previous echocardiographic studies (6,13) have shown that there is approximately a 5.5% increase in diameter during the systolic phase resulting in a 3 to 14% increase in cross-sectional area. The only study directly measuring aortic circumference variation during the cardiac cycle was an animal study by Loebel et al. (20), who documented a mean increase in aortic systolic area of 9%. The dual beam Doppler method measures the systolic cross-sectional area directly at the same site and at the same time that the aortic velocity is measured. Also, because the wide beam totally encircles the aortic cross-sectional area and the area is determined by flow, noncircular cross-sectional areas are measured accurately.

In previous systems (4,5,6,10,13,17), the greater the angle of insonation relative to the aortic flow vector, the greater
the compromise in mean velocity measurements. In most studies (4,5,10,19), the assumption was made that if this angle was \(<20^\circ\), the error of velocity estimation was within 6\% (\(\cos 20^\circ = 0.94\)). The dual beam Doppler method is angle independent. Because both velocity and cross-sectional area are measured at the same angle of incidence, the velocity measurement is underestimated by the same factor (\(\cos \theta\)) that the cross-sectional area is overestimated. Therefore, in the product of velocity and cross-sectional area, the \(\cos \theta\) factor cancels out and the final measurement is independent of the angle of insonation relative to the aortic flow vector.

Though difficult to measure, the sample size of previous Doppler systems (13) is relatively small, thus sampling within the center of the aorta. The assumption that the aortic flow profile was flat was accepted. Previous studies (18,21,22) have shown that the flow profile is nearly flat at the level of the aortic valve, but distal to this level slightly parabolic flow patterns are present with velocities maximal in the center of the aorta. With the dual beam Doppler system, the wide beam receives velocity information from the entire cross-sectional area of the ascending aorta. Therefore, a flat flow profile no longer has to be assumed and accurate velocity measurements can be attained.

**Potential errors and limitations of the current study.** As in all Doppler measurements, reliability and accuracy are dependent on the experience of the technician and his or her desire to optimize transducer placement. In this study, the Doppler technician, though knowledgeable in cardiovascular anatomy and function, was without previous experience in M-mode, two-dimensional or Doppler echocardiography. After 4 h of initial training, an average of four Doppler measurements were performed on 45 volunteers over a 2 week period before the start of this study. This learning curve period could be dramatically shortened for technicians who had previous Doppler ultrasound experience.

In this study, accuracy and reproducibility of the Doppler study were of primary concern. The length of each study varied widely depending on the ease of attaining adequate waveforms. When a patient was easily insonated, 3 to 5 min was adequate time to complete the study. When a patient was difficult to study, 30 to 40 min often was needed to complete the study. Doppler studies of this duration would certainly compromise clinical acceptance.

Because the suprasternal notch is the only ideal window to insonate the ascending aorta for Doppler studies, recent surgical wounds of the suprasternal notch and tracheostomy prevented Doppler cardiac output measurements. An obese neck often required greater transducer to skin pressure to direct the beam under the sternum. The measurement, however, could still be performed without undue patient discomfort. Anatomic variation of the chest wall, trachea or ascending aorta may occasionally prevent suprasternal notch transducers from insonating the ascending aorta. Doppler cardiac output measurements were successfully performed on 27 (90\%) of 30 patients on a mechanical ventilator. The endotracheal tube traverses a region very near the suprasternal notch and in 3 of the 30 patients the endotracheal tube appeared to totally obstruct the Doppler signal. In a few patients this interference occurred only during the ventilator-supported inspiration. Holding the ventilator inspiration for one respiratory cycle would often allow for adequate Doppler cardiac output measurements.

**Patients with aortic insufficiency, aortic stenosis or aortic valve replacement** were not included in the study because of the abnormal flow patterns and turbulence induced by an abnormal aortic valve. Future studies evaluating the use of

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**Table 2. Results of Previous Studies Using Aortic or Left Ventricular Outflow Tract Doppler Ultrasound to Estimate Cardiac Output**

<table>
<thead>
<tr>
<th>First Author</th>
<th>r</th>
<th>SEE</th>
<th>Slope</th>
<th>Intercept</th>
<th>Comparison</th>
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<tr>
<td>Sanders (6a)</td>
<td>0.78</td>
<td>810</td>
<td>0.81</td>
<td>900</td>
<td>Fick</td>
</tr>
<tr>
<td>Touche (7)</td>
<td>0.94</td>
<td>360</td>
<td>0.75</td>
<td>1130</td>
<td>Indicator D</td>
</tr>
<tr>
<td>Alverson (8)</td>
<td>0.98</td>
<td>220</td>
<td>1.07</td>
<td>-4</td>
<td>Fick</td>
</tr>
<tr>
<td>Goldberg (9)</td>
<td>0.91</td>
<td>600</td>
<td>0.86</td>
<td>700</td>
<td>Indicator D</td>
</tr>
<tr>
<td>Chandraratna (10)</td>
<td>0.97</td>
<td>420</td>
<td>0.96</td>
<td>410</td>
<td>Thermal</td>
</tr>
<tr>
<td>Dickinson (11)</td>
<td>0.94</td>
<td>470</td>
<td>0.94</td>
<td>260</td>
<td>Fick</td>
</tr>
<tr>
<td>Huntsman (12)</td>
<td>0.94</td>
<td>580</td>
<td>0.95</td>
<td>580</td>
<td>Thermal</td>
</tr>
<tr>
<td>Ihlen (13)</td>
<td>0.96</td>
<td>700</td>
<td>0.81</td>
<td>1080</td>
<td>Thermal</td>
</tr>
<tr>
<td>Ihlen (13)</td>
<td>0.90</td>
<td>700</td>
<td>0.82</td>
<td>210</td>
<td>Thermal</td>
</tr>
<tr>
<td>Labovitz (14)</td>
<td>0.85</td>
<td>990</td>
<td></td>
<td></td>
<td>Thermal</td>
</tr>
<tr>
<td>Lewis (15)</td>
<td>0.93</td>
<td>630</td>
<td>0.85</td>
<td>1100</td>
<td>Thermal</td>
</tr>
<tr>
<td>Magnin (16)</td>
<td>0.83</td>
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<td>0.60</td>
<td>2300</td>
<td>Thermal</td>
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<tr>
<td>Nishimura (4)</td>
<td>0.94</td>
<td>780</td>
<td>1.00</td>
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<td>Thermal</td>
</tr>
<tr>
<td>Loepky (17)</td>
<td>0.84</td>
<td>610</td>
<td>0.84</td>
<td>440</td>
<td>Fick</td>
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<tr>
<td>Average</td>
<td>0.91</td>
<td>621</td>
<td>0.87</td>
<td>756</td>
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</table>

D = dilution; other abbreviations as in Table 1.
the dual beam Doppler system in these settings should be undertaken.

Two patients with severe respiratory distress had unsuccessful Doppler studies. Severe respiratory distress causes excessive thoracic cage movement, preventing consistent focusing of the Doppler beam on the ascending aorta. One of the seven patients unsuccessfully studied had a markedly irregular supraventricular arrhythmia, that resulted in very erratic velocity measurements, therefore, consistent results could not be attained. Eight other patients with arrhythmias were included in this study. These patients exhibited a certain periodicity of their conduction abnormality and were included in the Doppler cardiac output measurement. Five of six studies on patients with an intraaortic balloon pump were successful. In one patient with an intraaortic balloon pump inconsistent Doppler waveforms prevented successful Doppler cardiac output estimation.

Potential error can be induced by nonsimultaneous measurement of noninvasive and invasive cardiac output. In the intensive care unit setting, the cardiac output is not always static. Both measurements were made within 10 min on patients in stable condition. On patients with significant fluctuations in blood pressure or heart rate, efforts were made to measure cardiac output with both methods simultaneously.

Noninvasive monitoring of the cardiac output during exercise has been previously attempted and adequate results have been attained with low to moderate grade exercise (23, 24). However, with more vigorous exercise the inability to consistently focus the Doppler beam on the ascending aorta has prevented reliable results. We have found similar limitations with the use of the dual beam Doppler system.

Potential uses. This study demonstrates that in the intensive care unit setting the cardiac output can be reliably measured by noninvasive methods. In this setting, the effects of cardioactive drugs and pacing therapy can be rapidly evaluated by serial measurements of the cardiac output. The noninvasive cardiac output method may also be used as a screening tool for patients who may need further invasive monitoring. The relative contributions of cardiac versus pulmonary decompensation in respiratory distress may be determined in the emergency room setting by a Doppler cardiac output. The noninvasive measurement of cardiac output in the office setting may be beneficial for the medical management of low cardiac output states. Noninvasive monitoring of cardiac output in the anesthetized patient may help to manage patients with wide fluid load fluctuations seen in major surgery. Finally, the noninvasive measurement of the cardiac output in clinical research may be of considerable benefit.

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References


