Determination of cardiac output by an angle and diameter independent dual beam Doppler technique in critically ill infants

Carl-F Wippermann, Dietmar Schranz, Ralf Huth, Fred Zepp, Hellmut Oelert, Bodo K Jüngst

Abstract

Objective—To compare cardiac output measurements in critically ill infants by the dual beam Doppler and thermodilution techniques.

Design—Prospective direct comparison of the two techniques. For statistical evaluation one randomly assigned paired measurement of every patient was used.

Setting—Paediatric intensive care unit in a university hospital.

Patients—18 infants after open heart surgery aged 4–25 months (weight 4–10 kg).

Interventions—Cardiac output measurements by dual beam Doppler and thermodilution techniques were performed within 10 minutes of each other and without knowledge of the results of the other methods. Multiple measurements were performed on some patients with a pharmacological or electrophysiological intervention or with a minimum of six hours between each pair of measurements.

Measurements and main results—Three patients were excluded because of an inadequate Doppler signal or a significant residual shunt. Cardiac output measurements ranged from 0·4 to 2·2 l/min for the thermodilution technique and from 0·5 to 2·1 l/min for the dual beam Doppler technique. Agreement between both methods was acceptable. The mean difference between the two methods was 0·026 l/min with two standard deviations ranging from −0·20 to 0·26 l/min.

Conclusion—The dual beam Doppler technique was shown to have promise for the non-invasive determination of cardiac output in critically ill infants.

Assessment of cardiac function is important in the evaluation and treatment of critically ill neonates, infants, and children. Cardiac output is usually measured by thermodilution or dye dilution techniques. These techniques, however, require insertion of a catheter into the pulmonary artery. 3, 4 They are complicated in neonates and infants because the arteries small size and are associated with low but measurable morbidity and mortality. Pulsed Doppler measurement of cardiac output has been proposed as a non-invasive method of measuring cardiac output in children and in adults. 3, 4 In critically ill patients technique was, however, reported to be unsatisfactory compared with the thermodilution method. 3, 4

The following factors are thought to contribute to the inaccuracy of the Doppler method:

(a) Incorrect determination of vessel diameter, which is subsequently squared to calculate the cross sectional area of the vessel. 3, 4

(b) Velocity measurements when the angle of insonation (θ) is >15° can significantly underestimate cardiac output, especially if a “blinded” technique is used in which a small angle θ is assumed. 5, 6

(c) Incorrect determination of the mean velocity by measurement of the velocity at only one point within the vessel. This velocity is used as the spatially averaged velocity assuming a flat velocity profile. It has been shown, however, that in both major arteries the velocity pattern changes. 10, 11

The dual beam Doppler system is supposed to avoid many of the limitations of cardiac output determination by conventional Doppler echocardiography 12–14 and a dual beam Doppler system is now available for infants and children. We have evaluated the accuracy of the dual beam device for measuring cardiac output in critically ill infants and children by comparing it with cardiac output measured by thermodilution.

Patients and methods

The study group consisted of 18 patients aged 4 to 25 months (mean 9–9 months) with a weight of 4·1 to 10 kg. The indication for cardiac output measurement by thermodilution was management after open heart surgery. Surgery included repair of an atrioventricular septal defect in four patients and closure of a ventricular septal defect in 11 patients. We repaired tetralogy of Fallot, double outlet right ventricle, and transposition of the great arteries in one patient each. The catheters were placed in during operation. Multiple measurements were made in some patients who had a pharmacological or electrophysiological intervention and in other patients who had a minimum of six hours between each pair of measurements.

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DUAL BEAM DOPPLER TECHNIQUE: 
PRINCIPLE OF OPERATION

A commercially available dual beam Doppler system (Quantascope, Vital Science) with a 4 MHz two element annular array transducer (paediatric probe) was used. The "attenuation compensated flowmeter"17 used for this technique consists of a non-imaging, dual channel pulsed Doppler system with two concentric ultrasound beams and this approach has been described extensively.13-14 Briefly, the first beam is a uniform wide beam, with a sample volume that totally encompasses the vessel lumen (fig 1). The second, a narrow beam, is wholly within the flowing blood and its area at any depth is known exactly. Because of the size of the narrow beam, the diameter of the ascending aorta should be at least 10 mm.

Mean velocity (\( V \)) is measured with the wide beam, which completely insonates the ascending aorta and thus determines the Doppler shift frequency of all erythrocytes passing through the aorta. Thus a constant velocity profile does not have to be assumed; \( V \) is then proportional to the mean Doppler shift frequency (\( F_d \)) divided by \( \cos \theta \) of the angle of insonation:

\[
\bar{V} \propto \frac{F_d}{\cos \theta}
\]  

(1)

The cross sectional area of the ascending aorta (\( A \)) is calculated from the intensity of the returned Doppler shift frequencies of the two beams. Because each erythrocyte contributes equally to this backscattered Doppler power, the Doppler power of the wide beam (\( P_w \)) is equal to the projected lumen area (\( A_p \)) multiplied by an unknown attenuation constant (\( K_a \)):

\[
P_w = A_p \times K_a
\]  

(2)

Because \( A_p \) is equal to \( A \) divided by \( \cos \theta \), equation (2) can be written as:

\[
P_w = A \times K_a \cos \theta
\]  

(3)

So in equation (2) the Doppler power of the narrow beam (\( P_n \)) equals the known area of the narrow beam (\( A_n \)) multiplied by the same attenuation constant \( K_a \):

\[
P_n = A_n \times K_a
\]  

(4)

A combination of equations (3) and (4) gives the cross sectional area \( A \) as:

\[
A = A_n \times \frac{P_w}{P_n} \cos \theta
\]  

(5)

Cardiac output (CO) is the product of \( \bar{V} \), \( A \), and heart rate (HR). Therefore combination of equations (1) and (5) gives, cardiac output as:

\[
\text{CO} = C \times A_n \times \frac{F_d}{\cos \theta} \times \frac{P_w}{P_n} \times \text{HR}
\]  

(6)

where \( C \) is a precalibrated attenuation constant.

The dual beam Doppler technique determines Doppler shift frequency, Doppler power return of the two beams, and heart rate. Equation (6) is used to calculate cardiac output (fig 1). Cardiac output measurements by this device are independent of the angle of insonation \( \theta \) and a separately determined cross sectional area.

DOPPLER CARDIAC OUTPUT MEASUREMENTS

The transducer was placed in the suprasternal notch and directed towards the ascending aorta. The transducer position and sample depth were optimised by the typical audio signal of aortic blood flow and by maximisation of the power return of the small beam. The power and velocity wave forms were evaluated with an online computer (Toshiba 3100). Dependent upon the heart rate of the patient, five to 15 beats were averaged and measurements of cardiac output, stroke volume, heart rate, and flow acceleration were obtained. The precision of cardiac output determination of the first 16 patients was limited to 0·1 l/min; with changed software it was improved to 0·001 l/min. Measurements were made without knowledge of the cardiac output by thermodilution.

MEASUREMENT OF CARDIAC OUTPUT 
BY THERMODILUTION

Cardiac output was measured by thermal dilution within 10 minutes of the Doppler determination of cardiac output without knowledge of those results and in an unchanged haemodynamic state. The study protocol consisted of three iced dextrose injections, which were averaged. Computation of cardiac output was done either with an Abbot Oximetrix 3 cardiac output computer or with the cardiac output module of the Mennen Medical Solo monitor system. The precision of cardiac output determination was limited to 0·1 l/min.
STATISTICAL ANALYSIS

For the statistical evaluation of the agreement between the measurements of cardiac output by thermodilution and dual beam Doppler techniques only one randomly assigned paired measurement of each patient was used. The mean of each pair of measurements, together with the difference between each pair, were determined and these were plotted against each other. Agreement between the two methods was estimated by calculating the mean difference between the two methods and two standard deviations (SD) as suggested by Bland and Altman.\textsuperscript{16} The difference between the two measurements of each pair was evaluated in absolute values and also as a percentage of the average cardiac output of each pair:

\[ \% \text{ difference} = \frac{(\text{CO thermodilution} - \text{CO Doppler})}{(\text{CO thermodilution} + \text{CO Doppler})} \times 100 \]

Reproducibility studies in adults showed that a difference of at least 15\% (with three determinations for one measurement) between successive measurements is necessary to indicate a significant change in cardiac output.\textsuperscript{17} For that reason percentage differences of >15\% between results from thermodilution and Doppler techniques were regarded as clinically meaningful.

To illustrate the whole scatter of differences, all pairs of measurements were also evaluated; although it is not total, these pairs show some independence because of the changes that occur in the patient’s clinical state between each pair of measurements.

Results

Three of the 18 patients were excluded—two because of an inadequate Doppler signal. One of the two had a residual left ventricular outflow obstruction with high blood flow velocities that caused aliasing. The other had transposition of the great arteries. The third patient was excluded because of a significant residual shunt, as shown by colour Doppler echocardiography and by an increase in oxygen saturation from the right atrium to the pulmonary artery. This would have caused an overestimation of cardiac output by the thermodilution method.

We obtained 96 pairs of measurements from the remaining 15 patients. Cardiac output determinations ranged from 0.5 to 2.1 l/min for the Doppler technique and from 0.4 to 2.2 l/min for the thermodilution method.

In the 15 pairs of measurements used for statistical evaluation, an acceptable agreement was found between the two methods, with a mean difference of 0.026 (2SD range -0.20-0.26) l/min (fig 2). The mean percentage difference between the methods was 1.9\% (2SD range -20.5-24.2\%) (fig 3). In one patient the percentage difference was >15\%. In four patients the percentage difference was borderline at about 15\%.

When all 96 pairs of measurements were used similar results were obtained (table, figs 2 and 3). In 13 pairs of measurements the percentage difference was >15\% and in another six this was borderline at about 15\%.

Discussion

In the group of critically ill children studied, cardiac output measurements by the dual beam Doppler and thermodilution methods showed acceptable agreement. This is the first study to evaluate the dual beam Doppler method in critically ill children. In adults as good, or better, results have been reported with the dual beam Doppler system in patients during cardiac catheterisation and in medical or surgical intensive care units.\textsuperscript{12-14} Two other studies in patients in intensive care found good correla-
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was not available in the early postoperative period. Colour Doppler echocardiography carried out later showed a residual shunt only in the one patient mentioned earlier, who was excluded from the study population.

The dual beam Doppler method is subject to several systematic errors. Unless the wide beam completely insonates the aorta cardiac output will be underestimated. Similarly the sample volume of the narrow beam has to be completely within the aorta, otherwise wide overestimation results. Furthermore, the wide beam may not reach the complete ascending aorta because of overlying lung tissue. On the other hand, the main or right pulmonary artery may also be partly insonated by the wide beam. Both of these factors will cause errors in calculated cardiac output. Because the Doppler power return of the two beams is used to calculate aortic cross sectional area, this calculation, as with conventional Doppler echocardiography, seems to be a source of possible major errors.

The problem may be aggravated when the dual beam Doppler technique is used over the whole paediatric age group. Another Doppler probe with larger sized beams may be needed for older children who are still too small for the adult probe. Premature infants with low and very low birth weight need a probe with even smaller beams.

We concluded that the dual beam Doppler technique is a simple and promising method to measure the ascending aortic blood flow non-invasively in critically ill infants. It seems especially useful in this age group, in which invasive cardiac output measurement is more difficult than in older children or the adult population. Further evaluation of this system including its use in older children is needed.

We thank Paul Seifert, PhD, for his advice in the preparation of the paper.

<table>
<thead>
<tr>
<th>Agreement between dual beam Doppler and thermodilution technique</th>
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<tr>
<td>Thermodilution vs Doppler</td>
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<tr>
<td>One pair of measurements per patient (n = 15)</td>
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<tr>
<td>All pairs of measurements (n = 96)</td>
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<tr>
<td>Mean difference (2SD)/(l/min)</td>
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<tr>
<td>0.026 (0.23)</td>
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<tr>
<td>0.018 (0.25)</td>
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<tr>
<td>Mean percentage difference (2SD) (%)</td>
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<tr>
<td>1.88 (22.36)</td>
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<td>0.65 (22.37)</td>
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</table>

cations between cardiac output measured by the dual beam Doppler and thermodilution techniques. It was also noted that in some patients significant differences between the two methods could be shown by bias analysis. In our study we found a considerable variation between results obtained by the two techniques: 95% of the percentage differences could be expected in the range -21% to 25%. In only one of the 15 paired measurements and in 13 of all paired measurements percentage differences >15% were found and these were considered to be clinically meaningful. In a recent study that compared cardiac output measured by conventional Doppler echocardiography and by thermodilution in critically ill children a percentage difference >15% between the two methods was noted in 45% of all measurements and a percentage difference >25% was evident in a quarter of the measurements. Compared with these results the dual beam Doppler technique seems to give a more reliable measure of cardiac output in critically ill children. This is probably owing to the elimination of possible errors of the conventional Doppler method, as mentioned previously. The accuracy of the dual beam Doppler technique could probably be increased by averaging three measurements as in the thermodilution technique. In this technique the difference between two successive determinations necessary to show a significant change in cardiac output can be reduced from 26% to 15% if an average of three measurements is taken.

None the less the accuracy of the thermodilution method in humans is not known exactly and minor alterations in technique can cause overestimation of cardiac output by as much as 58%. Even under optimum conditions in vitro the standard error is seldom less than 10%. In a recent reproducibility study only 70% of the differences were within 20% of the mean value. It has been concluded that the overall biological error of any method of cardiac output measurement is 15–20%. Both Doppler methods, when used from the supercentral notch, calculate cardiac output without coronary blood flow. This explains, at least to some extent, the underestimation of Doppler cardiac output measurements compared with the thermodilution method in this study. Furthermore, the thermodilution method might have overestimated cardiac output because of small residual shunts that are often present immediately after patch closure of ventricular septal defects and which subsequently close spontaneously. For most of our patients colour Doppler echocardiography

was not available in the early postoperative period. Colour Doppler echocardiography carried out later showed a residual shunt only in the one patient mentioned earlier, who was excluded from the study population.

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