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Continuous Wave Doppler Cardiac Output: Use in Pediatric Patients Receiving Inotropic Support

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SUMMARY. **Doppler estimates of cardiac output have been shown to correlate closely with invasive measurement of cardiac output in hemodynamically stable adults and children. However, this method has not been validated in hemodynamically unstable pediatric patients. To assess the accuracy of continuous wave Doppler echocardiography in pediatric patients with unstable hemodynamics, we performed 27 simultaneous Doppler and thermodilution comparisons in 12 pediatric patients receiving inotropic support and afterload-reducing agents. Doppler cardiac output was calculated using aortic diameter measured from long-axis two-dimensional echocardiograms at three different sites: the aortic valve anulus, the aortic root at the sinuses of Valsalva, and the ascending aorta. For all measurements, there was a close correlation between Doppler and thermodilution techniques. However the site of measurement of aortic diameter had a significant impact on the strength on the correlation and the variability between Doppler and thermodilution. The best correlation and least variability were obtained using the aortic valve anulus diameter ($r = 0.94$). On serial determinations, percent change in Doppler stroke volume correlated well with thermodilution stroke volume ($r = 0.87$) and was useful in detecting both direction and magnitude of change in thermodilution stroke volume. Despite the administration of positive inotropic and afterload-reducing agents, Doppler cardiac output is a useful method for estimating cardiac output in hemodynamically unstable pediatric patients.**

KEY WORDS: **Doppler echocardiography — Cardiac output — Thermodilution — Pediatric intensive care**

Measurement of aortic blood flow using Doppler ultrasonography provides a clinically useful noninvasive estimate of stroke volume and cardiac output. Validation studies in adults and in children have demonstrated a close correlation between Doppler and a variety of invasive methods of cardiac output measurement [1–4, 7–10, 12–16]. Studies performed in adult intensive care patients have demonstrated a good correlation between Doppler and thermodilution cardiac output [9, 15], but changes in hemodynamic state have been shown to affect the strength of the correlation [4, 10]. There has been limited experience with Doppler cardiac output in critically ill pediatric patients [13].

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When using Doppler techniques, flow is calculated as the product of mean velocity of blood flow and cross-sectional area. The optimal site of measurement of aortic diameter is at the site of Doppler sampling when using range gated pulsed Doppler. However, few studies have addressed the best site of measurement of aortic diameter when using continuous wave Doppler [7, 10, 13, 16], particularly in pediatric patients [13, 16].

For reliable measurement of mean velocity, aortic flow must be laminar and the aortic spatial velocity profile must be flat, i.e., the velocity must be equal at all points across the vessel lumen. It is generally assumed that the aortic velocity profile is flat although studies in experimental animals and man have demonstrated variations in the spatial velocity profile among individual subjects and between studies [11]. The effect of altered hemody-

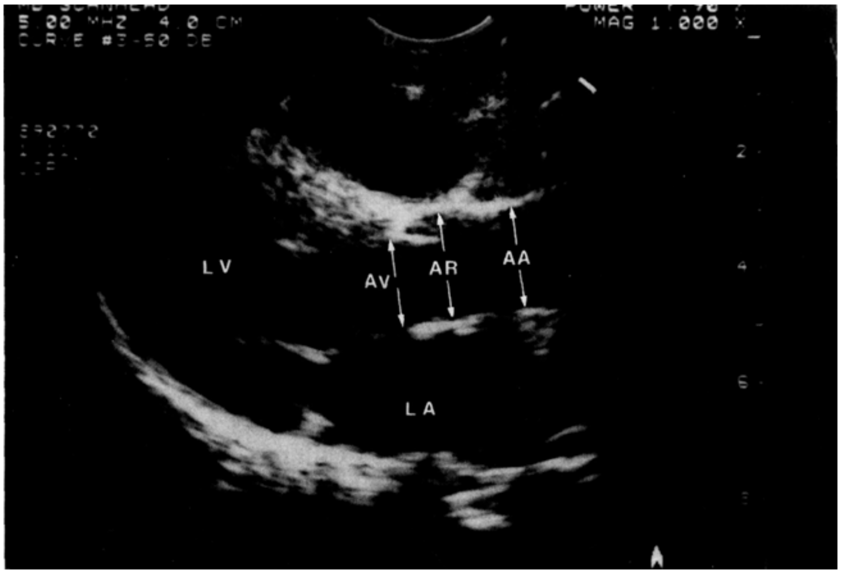

Fig. 1. Two-dimensional echocardiogram, parasternal long-axis view, illustrating the method of measuring aortic dimension. The internal dimension (trailing edge to leading edge) was measured in systole at three sites: the aortic valve anulus (*AV*), the aortic root (*AR*), and the ascending aorta (*AA*). *LA*, left atrium; and *LV*, left ventricle.

namics has only recently been addressed by Falsetti et al. [5], who demonstrated the development of turbulent aortic flow and skew in the aortic spatial velocity profile with the administration of a beta-adrenergic agonist (isoprenaline) in a canine model. Therefore, changes in hemodynamic state produced by administration of adrenergic agonists to unstable pediatric patients could lead to increased error in the measurement of cardiac output using Doppler.

The purposes of this study were: (a) to determine the accuracy of single and repeated continuous wave Doppler estimates of cardiac output compared with simultaneous thermodilution cardiac output in pediatric patients receiving inotropic support, and (b) to examine the effect of differences in site of measurement of ascending aorta diameter on the correlation of Doppler and thermodilution cardiac output and thereby determine the optimal site of measurement of aortic diameter.

Materials and Methods

Subjects

The study group consisted of pediatric intensive care patients with indwelling thermodilution cardiac output catheters. Patients with intracardiac or extracardiac shunts, aortic valve disease, or dysrhythmias were excluded from the study.

A total of 27 simultaneous continuous wave Doppler and thermodilution comparisons were performed in 12 patients, ranging in age from 7 months to 16 years (median = 24 months) and weight from 7 kg to 80 kg (median = 11 kg). Seven patients had multiple comparisons of Doppler and thermodilution cardiac output on different occasions, and five had single comparisons. Two additional patients were excluded because of inadequate two-dimensional imaging of the ascending aorta and aortic anulus. However, no subjects were excluded because of inadequate Doppler recordings.

Patients in this study had the following diagnoses: pneumonia (1), septicemia (2), near drowning (2), cardiomyopathy (3), head trauma (2), and postoperative repair of atrioventricular canal (2). All patients received positive inotropic agents (dobutamine and/or dopamine) and four were treated with afterload-reducing agents (nitroprusside or nitroglycerin) during the study. All subjects were mechanically ventilated with positive pressure ventilation. This study was performed with the approval of the Institutional Review Board on the Use of Human Subjects and, in each case, informed parental consent was obtained.

Echocardiographic Methods

An initial two-dimensional echocardiogram was performed in each patient, and the parasternal long-axis scan was used to determine aortic dimension (Fig. 1). Aortic diameter was measured in three locations: the aortic valve anulus, the aortic root at the sinuses of Valsalva, and the ascending aorta 1–2 cm above the sinuses of Valsalva. Videotaped images were frozen in systole, and measurements were obtained using the trailing-edge to leading-edge method with an off-line graphics analysis system. The average of three diameter measurements was used to calculate cross-sectional area at each location.

Continuous wave Doppler recordings were obtained from the suprasternal notch using a fast Fourier signal processing unit (Sonacolor model SC6300 CD) equipped with a 2.5-MHz nonimaging transducer. Maximal velocity was obtained by angling the transducer toward the ascending aorta and locating the peak velocity using the audio signal as well as the spectral display. A series of 5–10 consecutive cardiac cycles were used for analysis. Time velocity integrals were obtained by integrating the area beneath the velocity curve using a desk-top graphics analysis system. Stroke volume was calculated by multiplying the aver-

Table 1. Linear regression data for Doppler and thermodilution cardiac output

Aortic dimension	*n*	*r*	SEE
Aortic valve anulus	27	0.94	0.45
Ascending aorta	25	0.89	0.66
Aortic root	27	0.91	0.55

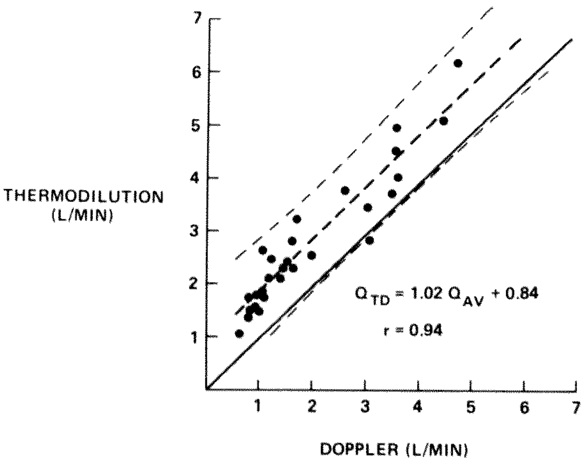

Fig. 2. Correlation of continuous wave Doppler and thermodilution (Q_{TD}) cardiac output with regression line and 95% prediction intervals (*broken lines*) and line of identity (*solid line*). Doppler cardiac output was calculated using aortic dimension measured at the aortic valve anulus (Q_{AV}).

age time velocity integral by aortic cross-sectional area, and cardiac output was calculated by multiplying stroke volume by heart rate.

Thermodilution

Simultaneous thermodilution and Doppler cardiac output determinations were performed by blinded observers. Four thermodilution cardiac outputs were performed using a thermodilution cardiac output computer with a 5-cc cold injectate administered at end inspiration. The first determination was discarded and the subsequent three were averaged.

Statistical Analysis

Results of the thermodilution and continuous wave Doppler cardiac output and stroke volume estimates were compared using simple linear regression analysis. Serial comparisons of percent change in Doppler stroke volume and thermodilution stroke volume were also compared using simple linear regression analysis.

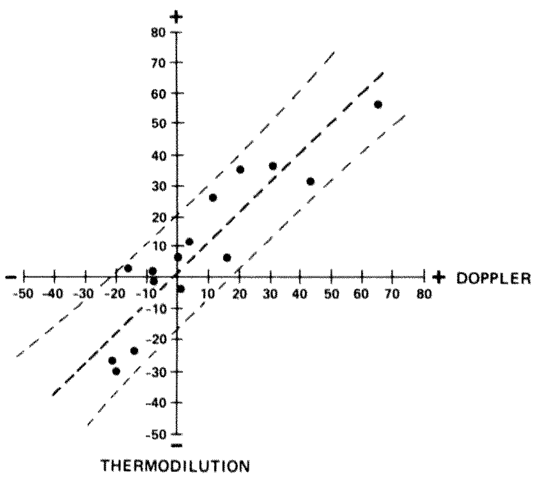

Fig. 3. Correlation of percent change in continuous wave Doppler stroke volume versus thermodilution stroke volume. *Broken lines* indicate the line of regression and 90% confidence intervals.

Results

There was a close correlation between Doppler and thermodilution cardiac output despite the administration of inotropic and afterload-reducing agents (Table 1). The best correlation (r = 0.94, slope = 1.02) was obtained when output was calculated using the aortic valve anulus dimension. Continuous wave Doppler cardiac output calculated using ascending aorta (r = 0.89) and aortic root (r = 0.91) diameters also correlated well with thermodilution cardiac output (Fig. 2). Wide prediction intervals were observed using all three measurements of aortic diameter. However, when comparing cardiac output calculated using these three different aortic diameters, the greatest variation was observed when area was calculated from the ascending aorta and aortic root diameters. Cardiac output calculated using the aortic valve anulus had the least variability and strongest correlation but consistently underestimated thermodilution cardiac output (intercept = 0.84 liter/min).

In serial determinations, percent change in Doppler stroke volume correlated well with percent change in thermodilution stroke volume (r = 0.87) and was useful in predicting both direction and magnitude of change in thermodilution stroke volume (Fig. 3). The Doppler method correctly predicted either no change or greater than 10% change in stroke volume in 12 of 15 comparisons. In two comparisons, Doppler stroke volume changed by >10% without a corresponding change in thermodilution stroke volume. In one case, thermodilution stroke volume changed by >10% without a corresponding increase or change in Doppler stroke volume.

Discussion

Correlation of Doppler and Thermodilution

Our initial experience comparing single and repeated measurements of Doppler cardiac output to thermodilution is encouraging. Although thermodilution cardiac output cannot be considered a "gold standard" [14], the frequent use of thermodilution in the intensive care setting makes thermodilution an appropriate method for comparison with Doppler. In the present study, the correlation between Doppler and thermodilution was close, despite the administration of inotropic and afterload-reducing agents. Our results are similar to those of others who have used suprasternal notch continuous wave Doppler to estimate cardiac output in adults [3, 9, 12, 14, 15] and children [13].

We found a marked effect on the correlation of Doppler and thermodilution cardiac output when aortic dimension was measured at different sites. Few studies have addressed the effect of variations in site of measurement of aortic diameter on the accuracy of Doppler cardiac output. In adults, Ihlen et al. [10] found the best correlation using pulsed Doppler and obtaining the diameter of the aorta at the aortic valve anulus. Gardin et al. [7] examined the effect of differences in site of measurement of aortic dimension on pulsed Doppler estimates of cardiac compared with thermodilution in adults. The best correlation was obtained using systolic internal diameter of the ascending aorta distal to the aortic root. The poorest correlation was obtained using M-mode echocardiographic measurement of the aortic root. Other investigators [3, 9, 12] have evaluated the use of continuous wave Doppler in adults using A-mode measurement of the smallest aortic diameter above the sinuses of Valsalva with good results, but have not evaluated the effect of differences in site of measurement of the aorta.

Most studies comparing the Doppler method to invasive measurement of cardiac output in children have used pulsed Doppler and have not evaluated the effect of different sites of measurement of aortic diameter. Alverson et al. [1] found an excellent correlation between ascending aorta pulsed Doppler and Fick estimates of cardiac output in pediatric patients undergoing heart catheterization, but the site of measurement of the ascending aorta was not specified. Goldberg et al. [8] found a close correlation using M-mode diameter of the aortic root and ascending aorta pulsed Doppler in pediatric catheterization patients while Sholler et al. [16] reported a close correlation between pulsed Doppler and indocyanine green cardiac output using maximal diameter of leaflet separation on M-mode echocardiography. In the present study, the best correlation with the least variation was obtained using the aortic valve anulus diameter (r = 0.94) in calculating stroke volume, although the correlation of Doppler and thermodilution cardiac output was good when output was obtained using the ascending aorta or aortic root diameters. Similar results were obtained by Rein et al. [13] although the correlation of Doppler and thermodilution was generally weaker in their study of pediatric intensive care patients.

Although the use of the aortic anulus diameter in calculating cardiac output resulted in the least variation and had a slope near unity, there was also a consistent underestimation of thermodilution cardiac output. There are several possible explanations for underestimation of cardiac output using the aortic valve anulus diameter: (a) The standard for comparison in this study was thermodilution cardiac output. At the end, inspiration thermodilution may overestimate cardiac output in patients on positive pressure ventilation [6]. (b) The angle between the direction of blood flow and the axis of the ultrasound beam when using suprasternal notch continuous wave Doppler is unknown. A large angle could lead to consistent underestimation of maximal aortic velocity and, thus, underestimation of cardiac output. (c) Flow are calculated from the aortic anulus diameter may actually be less than true flow area, and measurement of internal aortic anulus diameter from two-dimensional echocardiograms (trailing edge to leading edge) probably underestimates true aortic anulus diameter.

Sources of Variability

Although the relationship between Doppler and thermodilution estimates of cardiac output is linear, we observed significant variability about the line of regression between individual measurements obtained by the two methods. This degree of variability is comparable to that in other published reports [3, 4, 8, 15] and could be caused by many factors. Thermodilution cardiac output itself may vary from +16% to −17% in comparison to dye dilution cardiac output [6] and is highly subject to variations caused by differences in injection technique [17]. It is also possible that changes in afterload or inotropic state may lead to alterations in the spatial velocity profile or development of turbulent flow in the ascending aorta. Falsetti et al. [5] have described the development of turbulence and posterior skew in the aortic spatial velocity profile in mongrel dogs treated with isoprenaline. The development of turbulence or skew in the velocity profile in patients receiving inotropic agents would cause error in the measurement of mean velocity and, thus, produce error in the estimation of blood flow using Doppler. In addition, in low cardiac output or high resistance states, reduced acceleration can result in a parabolic rather than a flat velocity profile in the ascending aorta. Therefore, changes in hemodynamic state could result in variability in the measurement of maximal aortic velocity. It is significant that all the patients in this study received inotropic agents, and four received afterload-reducing agents. Despite the potential effects of changing hemodynamic state on the aortic velocity profile, the strength of the correlation and degree of variability that we observed is comparable to studies performed in hemodynamically stable patients. However, we cannot exclude the potential effect of adrenergic infusion on variability in the correlation between Doppler and thermodilution cardiac output, because patients were not studied prior to initiating therapy with inotropic or afterload-reducing agents.

Serial Measurements

The serial determination of cardiac output or stroke volume is perhaps the most clinically relevant application of Doppler techniques. Studies in children have emphasized single correlations obtained in the catheterization laboratory, but have not assessed the correlation of serial studies obtained under varying hemodynamic conditions. We examined the percent change in stroke volume determine by Doppler compared with thermodilution stroke volume in seven patients. As noted above, these patients were all receiving inotropic agents. In addition, during the period of study, many were subjected to other interventions, including changes in ventilator settings and introduction of afterload-reducing agents. However, despite changing loading conditions and inotropic state, the percent change in Doppler stroke volume correlated well with percent change in thermodilution stroke volume. In this clinical setting, we found continuous wave Doppler stroke volume useful in predicting both direction and magnitude of change (>10%) in stroke volume.

Conclusions

Continuous wave Doppler estimates of cardiac output obtained from the suprasternal notch correlated closely with thermodilution in pediatric intensive care patients receiving inotropic support. However, significant variability was observed between individual measurements of Doppler cardiac output and thermodilution cardiac output despite the close correlation between these two methods. The site of measurement of the ascending aorta greatly influenced the strength of the correlation and the degree of variability observed between Doppler and thermodilution cardiac output. The best correlation with the least variability was obtained using the aortic valve anulus dimension. In serial determinations in individual patients, percent change in Doppler stroke volume correlated well with thermodilution and was useful in detecting both direction and magnitude of change in stroke volume. Suprasternal notch continuous wave Doppler cardiac output is a useful noninvasive method for assessing changes in cardiac output in response to therapeutic interventions.

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