**Editorial Comment**

The Optimal Doppler Examination: Pulsed, Continuous Wave or Both?*

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**Introduction**

Doppler techniques permit accurate noninvasive determination of many hemodynamic variables; these include pressure gradients across valves, intracardiac and extracardiac stenoses and shunts (1–13), volume flow across valves (14–19) and valve areas (9,10,20–23). The excellent catheterization-Doppler correlations are most welcome but also somewhat surprising, given the inherent difficulty in Doppler examinations, the nonsimultaneous measurements in many of the correlative studies and the potential limitations of catheterization methods, particularly when fluid-filled catheters are used and pressure gradients calculated by pull-back techniques or measurement of peripheral arterial pressure.

Two papers in this issue of the Journal (24,25) further validate the accuracy of Doppler techniques in quantifying hemodynamic variables. Snider and coworkers (24) noted excellent correlations (all $r > 0.94$) between catheterization and Doppler measurements of valvular, subvalvular and intravascular pressure gradients in 41 children (mean age 6.2 years) undergoing Doppler study during catheterization. High pulse repetition frequency pulsed Doppler and continuous wave Doppler were equally capable of detecting high flow velocities. Marx et al. (25) studied 22 pediatric patients (mean age 4.5 years) with aortic-pulmonary shunts. They demonstrated an excellent correlation ($r = 0.94$) between pulmonary artery systolic pressure measured by strain gauge manometry and that estimated by subtracting the pressure gradient across the shunt, measured by continuous wave Doppler, from the systolic arterial pressure measured by cuff sphygmomanometry. They were unable to obtain optimal waveforms for measurement with standard pulsed Doppler techniques. Because instrument capabilities may be crucial in determining the results of Doppler study, this editorial will stress the differences between pulsed Doppler and continuous wave techniques, with emphasis on their advantages and limitations and on the potential for improved definition of physiologic abnormalities when the two are combined.

**Pulsed Doppler Echocardiography**

In pulsed Doppler echocardiography, the transducer samples only a small, operator-chosen area (sample volume) within the heart or great vessels. Generally performed with two-dimensional imaging using combined imaging-Doppler transducers, its major advantage is its ability to localize flow disturbances. Its major disadvantage is its inability, in many patients, to accurately quantify high flow velocities. In routine pulsed Doppler echocardiography, the maximal detectable kilohertz shift is one-half the pulse repetition frequency of the transducer (Nyquist limit) (23). The number of pulses emitted per second is dependent on the depth of the sample volume. When the sample volume is close to the transducer, a relatively short time is required for transmission and reception of sound waves, allowing a higher pulse repetition frequency than is possible with sample volume placement at greater depths. Because sample volume depths are generally much shallower in pediatric patients than in adults, higher flow velocities can generally be detected in children before aliasing occurs.

Several modifications of pulsed Doppler techniques may improve detection of high flow velocities (12). These include sampling flow at the shallowest possible depth, to increase transducer pulse repetition frequency, use of lower frequency transducers and alterations in the angle of Doppler interrogation, permitting use of angle correction techniques. Most clinicians, however, avoid angle correction methodology, because the angle between the Doppler beam and blood flow is difficult to predict, particularly in patients with distorted valves. If intercept angle is incorrectly predicted, pressure gradients will be overestimated (12,23). Changes in instrument design, including capacity to shift the central zero reference line and to add multiple sample volumes, to increase pulse repetition frequency, have permitted measurement of flow velocities of up to 5 m/s, without aliasing, in children (12). With multiple sample volumes, however, there is simultaneous transmission of more than one pulse within the patient. This can result in some ambiguity regarding origin of Doppler signals. Although successful detection of high velocities in adults has been reported by one laboratory (26,27), other laboratories, including our own, have experienced difficulty in quantitating high flow velocities with pulsed Doppler systems, including those with high pulse repetition frequency capability (2,11). Stewart et al.

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etition frequency units employ higher frequency transducers have been reviewed by Stewart et al. (2) and include the following:

1. Transit time effect: The short pulse may interrogate moving red cells for too short a period for adequate reflection of sound energy.

2. Frequency attenuation in tissue: Many high pulse repetition frequency units employ higher frequency transducers than do most continuous wave systems. Because higher frequency sound is attenuated more quickly with passage through tissue, a lower signal to noise ratio is expected.

3. Frequency-dependent attenuation in broadcast bandwidth: The broad frequency bandwidth produced by a pulsed Doppler transducer may cause the received signal to have a falsely low frequency shift, due to greater attenuation of high frequency components.

4. Decrease in energy emitted per pulse: With increasing frequency of pulsing, energy per pulse is decreased, reducing the signal to noise ratio.

5. Narrower beam profile of pulsed Doppler transducers: If the flow jet is narrow, it may be more easily missed by the pulsed Doppler beam than by the wider, continuous wave beam.

6. Necessity for the operator to position the sample volume at the correct depth along the axial beam.

7. Influence of transducer shape and size. This will be discussed later.

Continuous Wave Doppler Echocardiography

In a continuous wave examination, sound is continuously transmitted by one transducer and received by a second, adjacent transducer. Because the pulse repetition frequency of the continuous wave beam is essentially infinite, there is no theoretic limitation on maximal detectable velocity, and velocities of 6 m/s or greater have been recorded (1–5). This is the major advantage of the continuous wave transducer. In addition, because sampling occurs all along the axial beam and over a wide beam width, flow disturbances may be located more readily with continuous wave than with pulsed Doppler techniques.

The disadvantages of continuous wave Doppler study are lack of two-dimensional imaging for orientation, if a stand-alone transducer is used, and inherent range ambiguity resulting from recording of signals from the entire long and wide continuous wave beam. It may be difficult to distinguish between two jets located in spatial proximity to one another and having similar directional flow (24). Transducers that permit simultaneous imaging and continuous wave Doppler recordings and those measured at catheterization in adults with aortic stenosis, and they underestimated peak velocity by more than 0.5 m/s in 61% of high velocity lesions with high pulse repetition frequency pulsed Doppler compared with continuous wave techniques.

Potential reasons for underestimation of high flow velocities by high pulse repetition frequency pulsed Doppler have been reviewed by Stewart et al. (2) and include the following:

Usefulness of Combined Doppler Techniques

Optimal definition of cardiovascular pathophysiology requires both continuous wave and pulsed Doppler technology. Sites of turbulent flow can be spatially defined and differentiated by pulsed Doppler study. Velocity can then be best quantitated, at least in adults, by continuous wave techniques.

Accurate determination of aortic valve area is clinically very important. Transvalvular pressure gradients may provide insufficient information, particularly in adults with ventricular dysfunction, because they depend not only on valve area but also on duration and volume of transvalvular flow. Recently, analysis of semilunar jet velocity, by continuous wave technique, and of cardiac output, using imaging and pulsed Doppler echocardiography, has permitted accurate determination of aortic and pulmonary valve areas using a modification of the Gorlin formula (20). Alternatively, the equation of continuity, which states that volume flow in one area of the heart equals volume flow in another, in the absence of valvular regurgitation and shunt flow, can be used to calculate valve area (9,21,22). Skjaerpe et al. (9) described excellent catheterization-Doppler correlations using the following equation for noninvasive analysis: Aortic valve area = A × V/V', where A = left ventricular outflow tract area, assessed by imaging echocardiography, V = maximal flow velocity in the outflow tract just before acceleration of flow, measured by pulsed Doppler echocardiography and V' = peak flow velocity in the aortic jet, determined by continuous wave Doppler technique. The
validity of these techniques in assessing aortic valve area requires further confirmation, but these preliminary studies suggest that noninvasive evaluation of the severity of aortic stenosis is now feasible.

Additional Comments on Technique

Whether one employs continuous wave or pulsed Doppler techniques, or both, it must be recognized that reliable Doppler estimations of flow velocity, pressure gradients and restrictive areas depend on technical expertise in obtaining and recording Doppler signals. Maximal flow velocities are recorded when the Doppler beam is aligned parallel to flow. Although an angle of up to 20° between the sound beam and the direction of flow results in only a 6% underestimation of flow velocity, the pressure gradient will be more severely underestimated because it is proportional to the square of the flow velocity (23). The direction of the sound beam relative to flow cannot be accurately determined by imaging techniques, even in combination with real time color flow mapping, which permits visualization of the flow jet in only one plane. Investigators performing Doppler studies, therefore, must be prepared to spend the time necessary to search for signals with the highest audible pitch, maximal velocity and most clearly defined spectral envelopes. To ensure that the highest velocities have been detected, thorough Doppler examinations require the systematic use of multiple transducer positions and angles of interrogation. In the case of aortic valve stenosis in the adult, for example, a complete study should involve attempts to record flow velocities from the suprasternal notch, right and left supraclavicular areas, right and left parasternal regions, apex and subcostal area (1,3,4,6,9,10).

References