A New Method for Estimating Left Ventricular dP/dt by Continuous Wave Doppler-Echocardiography
Validation Studies at Cardiac Catheterization

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In this study, we explored the use of continuous wave Doppler-echocardiography guided by color Doppler flow-mapping as a method for noninvasively calculating the rate of pressure rise (RPR) in the left ventricle. Continuous wave Doppler determination of the velocities in mitral regurgitant jets allows calculation of instantaneous pressure gradients between the left ventricle and the left atrium. Left atrial pressure variations in early systole can be considered negligible; therefore, the rising segment of the mitral regurgitation velocity curve should reflect left ventricular pressure increase. We studied 50 patients (mean age, 51 years; range, 25–66 years) in normal sinus rhythm with color Doppler–proven mitral regurgitation and compared the Doppler-derived left ventricular RPR with peak dP/dt obtained at cardiac catheterization. Doppler studies were performed simultaneously with cardiac catheterization in 11 patients and immediately before in the remaining cases. Two points were arbitrarily selected on the steepest rising segment of the continuous wave mitral regurgitation velocity curve (point A, 1 m/sec, point B, 3 m/sec), and the time interval (t) between them was measured. Following the Bernoulli relation, the pressure rise between points A and B is 32 mm Hg (4vB²–4vA²) and the RPR is 32 mm Hg/t. Results showed a linear correlation between the Doppler RPR and peak dP/dt (r=0.87, SEE=316 mm Hg/sec). The RPR in the left ventricle can be derived from the continuous wave Doppler mitral regurgitation velocity curve. (Circulation 1989;80:1287–1292)

Continuous wave Doppler allows accurate determination of the instantaneous pressure gradients across stenotic valves1–6 as well as right-sided regurgitant lesions,7–9 by means of the simplified Bernoulli equation.1,2 In a recent study, Nishimura et al10 have demonstrated that continuous wave Doppler is also accurate in measuring pressure gradients in left-sided regurgitant valves.

Peak dP/dt is one of the most commonly used indexes for assessing left ventricular function. To date, the use of continuous wave Doppler-echocardiography in the noninvasive calculation of the rate of pressure rise (RPR) in a cardiac chamber has not been validated. Continuous wave Doppler determination of the velocities of a mitral insufficiency jet should allow calculation of instantaneous pressure gradients between the left ventricle and left atrium. Compared with the major changes in left ventricular pressure, left atrial pressure variations in early systole can be considered negligible, even in the presence of mitral insufficiency. Therefore, the rising segment of the mitral insufficiency velocity curve should reflect left ventricular pressure elevation. The purpose of our study was to evaluate the accuracy of continuous wave Doppler-echocardiography guided by color Doppler flow-mapping as a method for noninvasively calculating the left ventricular RPR.

Methods

Patient Population

Fifty patients in normal sinus rhythm with mitral regurgitation during color Doppler flow-mapping examination were studied. All patients underwent
Continuous wave Doppler-echocardiography, color Doppler flow-mapping, and left heart catheterization. Eight patients were excluded because of an inadequate Doppler examination. As a result, the final study population consisted of 42 patients (33 men, nine women; mean age, 51.2 years, range 25–66 years). Of these patients, 23 had coronary heart disease (defined angiographically as ≥50% luminal diameter narrowing of at least one major coronary artery), 12 had rheumatic heart disease, and seven had dilated congestive cardiomyopathy. Thirty-five patients had pure mitral regurgitation; seven had combined mitral regurgitation and mitral stenosis; seven patients had associated aortic regurgitation; and one patient had associated aortic stenosis.

Doppler Examination

The equipment used was a phased-array, real-time, two-dimensional Toshiba SSH65 flow-imaging system operating with a 2.5-MHz transducer. Each patient was examined while in a lateral recumbent position. The studies were performed from standard apical four-chamber views using a 45° color sector and 4-KHz pulse-repetition frequency. Continuous wave Doppler frequency shifts were analyzed and displayed at 2-msec intervals. This instrumentation is capable of imaging in real time the spatial distribution of the regurgitant jet and, therefore, allows guided continuous wave Doppler interrogation to be performed. During the examination, the Doppler beam was oriented parallel to the direction of the mitral regurgitant jet, as seen by color Doppler flow-mapping. Afterward, minor manipulations of the transducer were performed until the highest continuous wave Doppler jet velocity was recorded. Alignment was considered good when the angle between the Doppler beam and the regurgitant jet was less than 20°. The continuous wave maximal jet velocity was converted to left ventricular–left atrial pressure gradient by the simplified Bernoulli equation (see below). Peak pressure gradient was compared with arm-cuff blood pressure: if the difference was more than 20 mm Hg the patient was excluded from the study. In the patient with associated aortic stenosis, the accuracy of the alignment was indicated only by color Doppler visualization of the jet. Eight patients were excluded because it was impossible to align the Doppler beam with the direction of the jet. Doppler examination was performed simultaneously with cardiac catheterization in 11 patients (micromanometer-tipped catheter) and just before catheterization in the remaining patients. In the latter patients, the clinical status did not change during the interval.

Doppler Measurements

Continuous wave Doppler tracings of mitral regurgitation velocity curves were recorded on a Panasonic AG-6200 videocassette recorder at a sweep speed of 100 mm/sec. All Doppler measurements were performed directly from the video screen by means of the software program incorporated in the equipment, using a trackball for tracing. The instantaneous pressure drop between the left ventricle and the left atrium was calculated from the modified Bernoulli relation: \[ \Delta P = 4v^2 \], where \( \Delta P \) is the pressure drop (mm Hg) and \( v \) is the instantaneous regurgitant jet velocity (m/sec). Two points were arbitrarily selected on the steepest ascending segment of the continuous wave mitral regurgitation velocity curve (point A, 1 m/sec=4 mm Hg; point B, 3 m/sec=36 mm Hg), and the time interval (t) between them was measured. Pressure rise between A and B is 32 mm Hg; RPR is 32 mm Hg/t (Figures 1 and 2).

For each study, measurements were obtained from five cardiac cycles; the five cycles chosen for analysis were those with the highest velocity peak. Reproducibility of the Doppler variable, \( t \), was evaluated in 16 randomly selected patients. To assess intraobserver variability, one investigator measured the same set of five cardiac cycles in each patient on two occasions (2 weeks apart), while interobserver variability was examined by having two investigators measure the same set of cardiac cycles in each patient. All observers were blinded to each other’s results as well as the results of cardiac catheterization. The correlation between measurements for the same observer \((r=0.99;\ SEE=1.46\ msec;\ mean\ difference=0.56\ msec)\) and that between observers \((r=0.99;\ SEE=1.77\ msec;\ mean\ difference=1.19\ msec)\) was excellent.

Catheterization

Premedication consisted of 10 mg diazepam given orally 1 hour before catheterization. Catheters were
inserted through a right median antecubital or femoral percutaneous incision. In 22 patients, left ventricular pressure was measured with an 8F micromanometer-tipped catheter (Millar Instruments). The micromanometer system was calibrated electronically after equilibration against the pressure recorded through the fluid-filled catheter. The zero-pressure reference was set at midchest. In the remaining patients, well-flushed 7F or 8F fluid-filled catheters connected to a strain-gauge pressure transducer were used. Peak left ventricular dP/dt was obtained by electronic differentiation of the left ventricular pressure pulse. Pressure tracing was recorded at 250 mm/sec paper speed.

Severity of regurgitation was graded according to the classification of Sellers et al\textsuperscript{11}: 1+ (mild), 2+ (moderate), 3+ (moderate to severe), and 4+ (severe).

**Statistical Analysis**

Data are expressed as mean±SD. Comparisons of measurements of heart rate and blood pressure were made with the Student’s \( t \) test for paired samples. The level of statistical significance was defined at \( p \leq 0.05 \). A linear regression analysis was used to compare the catheter-measured peak dP/dt and the Doppler-derived RPR.

**Results**

There were no statistically significant differences in heart rate (\( p > 0.05 \)) or systolic and diastolic blood pressure (\( p > 0.05 \)) between the noninvasive measurements and those taken at the time of cardiac catheterization in the patients studied nonsimultaneously. In five patients, left ventriculography did not detect mitral regurgitation. Of the remaining

*Figure 2. Continuous wave Doppler recordings of the mitral regurgitation velocity curve in two patients. Panel A: Normal left ventricular function (\( t \) is 15 msec, corresponding to a rate of pressure rise (RPR) of 2,133 mm Hg/sec). Panel B: Depressed myocardial function in dilated congestive cardiomyopathy (\( t \) is 56 msec, corresponding to an RPR of 571 mm Hg/sec). On the right, color Doppler systolic still frame showing the optimal alignment between continuous wave Doppler beam and regurgitant jet.*
patients, 20 had mild mitral regurgitation, 12 had moderate, three had moderate to severe, and two had severe mitral regurgitation.

The peak dP/dt ranged from 589 to 2,751 mm Hg/sec (mean, 1,373 mm Hg/sec) by catheterization, and the RPR ranged from 410 to 2,601 mm Hg/sec (mean, 1,285 mm Hg/sec) by Doppler. A good correlation was seen for the entire patient population between the catheterization-measured peak dP/dt and the RPR within the left ventricle estimated by continuous wave Doppler ($r=0.87$; SEE=316 mm Hg/sec; slope=1.05) (Figure 3). Separating the patients with no or mild angiographic mitral regurgitation from those with moderate to severe regurgitation revealed a good correlation for both groups (Figure 4). The correlation coefficient of the subset of patients in whom a micromanometer-tipped catheter was used was 0.91 (SEE=288

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**Figure 3.** Plot of correlation between Doppler-derived rate of left ventricular pressure rise (RPR) and catheter-determined peak dP/dt in the 42 patients. ▲, Fluid-filled catheters; ●, Millar catheters; ○, Millar catheters (simultaneous study). Solid line represents regression line; dotted line, line of identity.

**Figure 4.** Plots of correlation between Doppler-derived rate of pressure rise (RPR) and catheter-determined peak dP/dt in patients with no or mild mitral regurgitation at angiography (left) and in patients with moderate to severe mitral regurgitation (right). ▲, Fluid-filled catheters; ●, Millar catheters; ○, Millar catheters (simultaneous study). MR, mitral regurgitation.
mm Hg/sec). This was significantly higher than in the fluid-filled catheter subset \((r=0.77,\ SE=354\ \text{mm Hg/sec})\) (Figure 3).

**Discussion**

Mitral regurgitation is a common finding in patients with a variety of cardiac disease states.\(^{12-16}\) Thus, a method for approximating left ventricular peak dP/dt based on Doppler-detected mitral regurgitation might be widely applicable.

In our study, we analyzed mitral regurgitant flow velocity patterns to calculate noninvasively the RPR in the left ventricle. The mitral regurgitant flow velocity pattern, recorded by continuous wave Doppler echocardiography, is characterized by a rapid increase in flow velocity immediately after closure of the mitral valve, followed in turn by a rapid deceleration. Hatle and Angelsen\(^{17}\) first suggested that a slower rate of rise of the left ventricular systolic pressure is indicated by the slower increase in velocity of the mitral regurgitation velocity curve. Our study demonstrates that a reliable estimate of the left ventricular RPR is possible from the mitral regurgitation velocity curve (Figure 3). We found a good correlation between the Doppler-derived left ventricular RPR and peak dP/dt both in patients with no or mild mitral regurgitation and in those with more severe mitral regurgitation (Figure 4).

As with other Doppler techniques that quantitate velocity, the Doppler beam must be aligned parallel to the velocity vectors downstream from the valve. Failure to align properly leads to underestimation of true velocity and, hence, underestimation of the RPR. Recently, preliminary reports have demonstrated that color Doppler flow-mapping permits accurate alignment between the continuous wave Doppler beam and stenotic or regurgitant jets.\(^{18,19}\) Therefore, great care was taken to achieve the smallest possible angle between the Doppler beam and the direction of the regurgitant jet, as visualized by color Doppler flow-mapping. The accuracy of the alignment was confirmed by the small difference between the arm-cuff blood pressure and the Doppler-estimated left ventricular pressure \((<20\ \text{mm Hg in all patients but one with aortic stenosis}).\)

Continuous wave Doppler determination of the velocities of the mitral regurgitant jet allows calculation of instantaneous pressure gradients between the left ventricle and the left atrium following the simplified Bernoulli relation. The maximal velocity in mitral regurgitation depends only on the pressure difference between the chambers and is independent of the size of the orifice.\(^{20}\) Even in the presence of mitral regurgitation, left atrial pressure variations can be assumed to be negligible for a short period of time in early systole. Therefore, the rising segment of the mitral regurgitation velocity curve would reflect the pressure variations within the left ventricle. The Doppler equipment used offers high temporal resolution and is used for the study of rapidly changing velocities. Doppler studies were relatively easy to perform from the apical approach in subjects at rest. We were able to obtain adequate Doppler tracings in 84% of the patients studied. In the majority of our cases, the degree of regurgitation was mild or moderate; also, it is interesting to note that in five cases without angiographic evidence of mitral regurgitation, it was possible to obtain the continuous wave Doppler velocity curve of the regurgitant jet.

A potential source of error in data acquisition in most of our patients was the use of non simultaneous catheterization data for correlation with the Doppler-predicted RPR. However, Doppler examination was performed just before cardiac catheterization, and no patient presented significant changes in heart rate or blood pressure between the two studies. Therefore, the errors introduced by the time interval between measurements would not be excessive. In a significant portion of our cases, pressure recordings were obtained by means of a fluid-filled catheter. Several authors in previous studies used similar catheter systems with satisfactory results.\(^{21-24}\) However, such catheters have been known to introduce potential distortions of pressure pulses. The correlation between Doppler-derived RPR and peak dP/dt at catheterization was closer for the subset in which a Millar catheter was used than in the fluid-filled subset. This may be due partly to the more reliable recordings of the left ventricular pressure curve being obtained with high fidelity catheters; moreover, in 11 patients studied with the Millar catheter, Doppler and hemodynamic data were obtained simultaneously.

In a substantial number of patients, especially those with low catheter-derived dP/dt, we underestimated the true values. This underestimation may be explained in part by the fact that this Doppler method provides a mean RPR. The use of new systems capable of deriving peak acceleration (first differential of velocity and, hence, maximal RPR) may circumvent this problem.

**Clinical Implications**

Although the maximal left ventricular RPR (peak dP/dt) is dependent to some extent on preload and afterload,\(^{25}\) it is one of the most commonly used indexes in the study of directional changes of contractility in patients.

In the presence of mitral regurgitation, the validity of isovolumic indexes as indicators of contractility is questioned. Nevertheless, various authors have argued that mitral regurgitation appears to have little effect on the accuracy of the determination of dP/dt-derived isovolumic indexes.\(^{21-23,26}\) Peak dP/dt has been used to evaluate acute changes in contractility in experimental animals with mitral regurgitation\(^{27-29}\); moreover, a change in peak dP/dt is a commonly used reference for determining alterations in myocardial contractility in patients with congestive heart failure. It would seem impractical, however, to perform invasive measurements repeat-
edly in a given patient, and in the great majority of these cases it is possible to detect mitral regurgitation by Doppler. The major advantage of this new Doppler method is that it provides a noninvasive estimation of the RPR on a beat-by-beat basis, which should make it ideal for serial measurements in patients with mitral regurgitation.

In conclusion, the results of this study suggest that the left ventricular RPR can be calculated accurately from continuous wave Doppler recordings of mitral regurgitation velocity curves. This method provides new noninvasive information concerning left ventricular function. Other studies are needed to assess the sensitivity of this method in detecting changes of myocardial contractility.

References


KEY WORDS • echocardiography, Doppler • ventricular function • valvular regurgitation
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Circulation. 1989;80:1287-1292
doi: 10.1161/01.CIR.80.5.1287

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