Quantification of Mitral Regurgitation With Amplitude-Weighted Mean Velocity From Continuous Wave Doppler Spectra

Rolf Jenni, MD, Manfred Ritter, MD, Franz Eberli, MD, Joerg Grimm, PhD, and Hans P. Krayenbuehl, MD

Amplitude-weighted mean velocity from continuous wave (CW) Doppler spectra was used to measure aortic flow ($Q_A$) and left ventricular mitral inflow ($Q_{LVI}$). These flows were used to quantify mitral regurgitation fraction: $$RFm = (Q_{LVI} - Q_A) \cdot Q_{LVI}^{-1} \cdot 100\%.$$ $Q_{LVI}$ was calculated from the diastolic time integral of amplitude-weighted mean velocity that was derived from CW spectra with the transducer placed in the apical window and the CW beam directed toward the left ventricular inflow tract. $Q_A$ was obtained from the systolic time integral of amplitude-weighted mean velocity by using the same apical window and directing the CW beam toward the left ventricular outflow tract. In 20 normal subjects, RFm ranged between -6.2% and +8% (mean, -0.8%). In 25 patients with pure mitral regurgitation, RFm obtained by Doppler ($y$) was compared with RFm calculated from biplane left ventriculography and the Fick method ($x$). The correlation was $r=0.96$, SEE=6.1% of the mean or 12% of the angio-Fick mean; the regression line was $y=0.96x+0.18$; mean $y=49\%$, mean $x=51\%$. It is concluded that RFm can be determined accurately by using amplitude-weighted mean velocities from CW Doppler spectra. The advantages of this method are its independence from the measurement of the left ventricular inflow or outflow tract area. (Circulation 1989;79:1294–1299)

Diagnosis of valvular regurgitation by Doppler echocardiography is characterized by excellent sensitivity and specificity despite some technical limitations inherent to the method.\(^8\)

Quantitative assessment of valvular regurgitation, however, has proven to be more problematic. The methods used so far have focused on the use of the velocity information contained in the pulsed Doppler signal and the determination of the anulus area to determine regurgitant volume or regurgitant fraction.\(^2,5,7,9,10\) Inherent to this type of approach are difficulties in determining the mean velocity within the cross section and knowing exactly where to measure cross-sectional area, which represents a major constraint for the absolute determination of blood flow volumes by Doppler echocardiography.\(^11,12\) Mapping of the spatial extent of the flow disturbance in the regurgitant chamber with pulsed Doppler\(^9\) or color Doppler\(^11,13\) is a semiquantitative approach to determine the degree of valvular regurgitation.

The aim of this study is to present a novel method for quantification of mitral regurgitation based upon the calculation of the systolic or diastolic time integral of amplitude-weighted mean velocity from continuous wave Doppler spectra obtained in 20 volunteers and in 25 patients with various degrees of mitral regurgitation.

Methods

**Basic Principle**

In contrast to conventional Doppler techniques used to assess blood flow rates from cross-sectional vessel area and mean velocity within the vessel, the approach applied in this study is based on the following physical principles.

The backscattered power (square of the amplitude of the received signal) from the erythrocytes at a particular Doppler frequency represents a measure of the number of erythrocytes moving at the corresponding velocity within the ultrasonic beam. If the scattering particles are randomly distributed, the power spectrum is proportional to the number of scattering particles.\(^14\) In normal blood, the volume concentration of the erythrocytes is approxi-
mately 45%; this means that each scattering particle will be in contact with one or more of the other particles at each instant of time. Therefore, the assumption of noninteracting scattering particles will not hold.\textsuperscript{15} In this situation of a nonrandom distribution of the backscattering particles, the amplitude of the Doppler signal is proportional to the number of scattering particles.\textsuperscript{16} The sum of the individual velocities of the particles within the Doppler spectrum multiplied by their respective signal amplitude is called amplitude-weighted mean velocity (AWMV) and is proportional to instantaneous blood flow:

\[ Q_{-\text{AWMV}} = \int_{f_{c}}^{f_{c}} A(f) \cdot f \cdot df \quad (1) \]

where \( Q \) is volume flow rate, \( A(f) \) is amplitude spectral density, \( f \) is Doppler shift, \( f_{c} \) is spectral range, and \( f_{c} \) is cut-off frequency of the wall filter.

The time integral of the AWMV is proportional to the blood flow volume during a given time interval. To gather all the signals from the scattering particles passing through the mitral or aortic orifice, it is essential that the continuous wave beam homogeneously interrogates the whole area of the respective anulus. Ideally, the AWMV in a thin layer within the orifice of interest, that is, the aortic or mitral anulus, respectively, should be used for the assessment of blood flow volume rates. The Doppler signal measured with continuous wave mode stems from all scattering particles positioned within the intersection of the transmitting and receiving ultrasonic field. Thus, the Doppler signal not only comes from scattering particles within the valve area but also from particles within the left ventricle and blood distal to the anulus region as well as some stationary scattering particles. Low-pass filtering eliminates contributions from stationary scattering particles as well as parts of the signals from the left ventricle, which contains a considerable fraction of slowly moving scattering particles. Thus, low-pass filtering essentially confines the volume of interest to the fast flowing scattering particles in the area of interest close to the aortic or mitral valve.

Sound waves are attenuated exponentially with increasing distance from the transducer. This reduces the signal amplitude scattered from the valve area relative to the signal from the near field within the left ventricle. Because the distance of the aortic and mitral anulus from the apical transducer position are very similar, the attenuation factor is approximately equal for both measurements.

**Equipment**

A real time phased-array sector scanner (HP 77020, Hewlett-Packard, Andover, Massachusetts) was used to present echocardiograms and continuous wave Doppler signals. The software was modified by the manufacturer to include Equation 1 for calculation of AWMV. The duplex transducer contained a 2.5-MHz crystal set for imaging and a 1.9-MHz crystal set for continuous wave Doppler.

The half maximum width of the continuous wave beam, measured in a water bath, is 13 mm at a distance of 10 cm, 18 mm at a distance of 15 cm, and 26 mm at a distance of 20 cm. This applies to lateral direction as well as elevation. Low-pass filtering was accomplished with a 200-Hz filter in all study participants and was not modified throughout the study to avoid induction of additional variation on the computations of AWMV.

**Recordings**

Blood flow volume rates were measured at identical amplification both in the left ventricular inflow tract and in the aorta with the transducer placed in the apical position. The cursor position of the continuous wave beam was superimposed on the sector image and directed parallel to the axis of blood flow until the highest frequency shifts of the continuous wave spectrum were achieved. AWMV was superimposed over the continuous wave spectrum in real time display. The continuous wave spectrum, the AWMV, and the electrocardiogram were recorded simultaneously on VHS video tape. The time integral of the AWMV curve over individual cardiac cycles was planimetered with a track ball system. For final comparison of the systolic (aorta) and diastolic (left ventricular inflow tract) time integrals of the AWMV, the corresponding four beats with the highest amplitudes were averaged.

**Patient Population and Evaluation of the Method**

In 20 healthy volunteers aged between 29 and 66 years Doppler echocardiographic variables were measured in the left ventricular inflow tract to assess diastolic blood flow volume rates through the mitral valve (\( Q_{L\text{Vin}} \)). The same measurements were made in the aorta to assess systolic blood flow rates through the aortic valve (\( Q_{A0} \)). To evaluate the validity of the concept of AWMV as a relative measure of blood flow volume rates, the mitral regurgitant fraction (RFm), which is expected to equal zero in normal individuals, was calculated as

\[ \text{RFm} (%) = \left( Q_{L\text{Vin}} - Q_{A0} \right) \cdot Q_{L\text{Vin}}^{-1} \cdot 100. \]

Thus, Doppler echocardiographic assessment of RFm in normal individuals permitted an in vivo evaluation of the method independent of any other method.

In 25 patients aged between 29 and 75 years with various degrees of pure mitral regurgitation RFm was determined as described above by Doppler echocardiography and compared with the angio-Fick procedure.\textsuperscript{17} In all patients, diagnostic cardiac catheterization was conducted during the same day of the echocardiographic examination.

Twenty patients who underwent diagnostic catheterization had mitral regurgitation from mitral valve prolapse and atypical chest pain, two patients were examined invasively because of clinically suspected coronary artery disease and mitral regurgitation, two patients had clinical symptoms of dilated car-
diomyopathy and mitral regurgitation, and one patient was catheterized because of clinically suspected severe mitral regurgitation due to endocarditis. Biplane left ventriculography was used to determine total angiographic stroke volume (TSV); forward stroke volume (FSV) was assessed by the Fick procedure with table values for the calculation of body oxygen consumption. Mitral regurgitant fraction as determined by the angio-Fick procedure was defined as \( \text{RFm}_{\text{AF}} = \frac{(\text{TSV}-\text{FSV}) \cdot 100}{\text{TSV}} \).

**Statistical Analyses**

The data were statistically evaluated by paired Student’s *t* tests and simple linear regression analysis.

**Results**

**Normal Individuals**

In the 20 normal individuals, RFm was calculated from the average AWMV values measured in the left ventricular inflow tract during diastole and in the aorta during systole. The values ranged between −6.2% and +8% (mean±SEM, −0.84±0.97%) (Figure 1).

**Patients With Mitral Regurgitation**

In the 25 patients with pure mitral regurgitation, Doppler echocardiographic RFm (y) correlated well to \( \text{RFm}_{\text{AF}} \) obtained from the angio-Fick procedure (x) (Table 1, Figure 2). The correlation coefficient was 0.96; the SEE was 6.1% of the mean, or 12% of the angio-Fick mean. The regression line was

\[
y = 0.96x + 0.18
\]

The mean regurgitant fraction determined by AWMV measurements was 49.3%; the mean regurgitant fraction from angio-Fick measurements was 51.0%.

**Discussion**

Quantification of mitral regurgitation requires determination of left ventricular total stroke volume and forward stroke volume. The major invasive technique currently used to assess total stroke volume is biplane left ventricular cineangiography and the technique used to determine forward stroke volume is indicator dilution, such as thermodilution, dye dilution, or the Fick method. Conventional Doppler echocardiographic methods quantify mitral regurgitation by determination of volumetric flow through the mitral and the aortic orifice. Volumetric flow is assessed from pulsed Doppler velocity measurements within the orifice area and calculation of the respective cross-sectional area from the two-dimensional echocardiographic image. This type of noninvasive approach is, however, subject to several major technical limitations. The determination of accurate mean blood flow velocity within the cross-sectional area and the precise measurement of the corresponding cross section, especially that of the elliptically shaped mitral orifice, prove to be rather critical and time consuming. These types of analysis are, therefore, not well suited for clinical routine applications. Semiquantitative noninvasive methods to assess mitral regurgitation are color Doppler flow mapping and pulsed Doppler mapping of the regurgitant jet.

In the present study, a novel method is used to quantify mitral regurgitant fraction, with AWMV from continuous wave Doppler spectra. To evaluate the validity of this new technique, it was first tested in 20 normal individuals, in whom regurgitant fractions are expected to equal zero. This allowed a validation independent of any other method. RFm obtained in the 20 normal individuals ranged from −6.2% to +8% (mean, −0.8%). In these individuals, the maximum error of the Doppler technique in determining the ratio of \( Q_{av}/Q_{LVOT} \), which represents a ratio of the relative stroke volumes in the aorta and the left ventricular inflow tract, was 8%. In
Table 1. Doppler and Angio-Fick Data

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<tr>
<th>Patient</th>
<th>Age</th>
<th>Gender</th>
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<td>F</td>
<td>ENDOC, MR</td>
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Mean 56  72  125  78  49  74  51  122  68
±SD 11  12  13  8  21  10  21  16  10

BP, blood pressure; RFm, mitral regurgitant fraction determined by amplitude-weighted mean velocity or invasively by the angio-Fick method; M, male; F, female; MVP, mitral valve prolapse; MR, mitral regurgitation; CAD, coronary artery disease; DCMP, dilated cardiomyopathy; ENDOC, endocarditis; SR, sinus rhythm; AF, atrial fibrillation.

*p<0.001.

Comparison, the ratio of the angiographically determined total stroke volume and the Fick-determined forward stroke volume in individuals without regurgitation was affected by a maximum error of 15%.20

In 25 patients with pure mitral regurgitation, RFm assessed from AWMV measurements was compared with the invasive RFm1.2. The good correlation of r=0.96 and a mean regurgitant fraction of 49.3% versus 51.0% document an excellent agreement of the new technique with the reference method, although afterload conditions, especially diastolic blood pressure, were slightly but significantly lower during catheterization than during the Doppler echocardiographic recordings. Of note also, the presence of mitral valve prolapse or a different origin of mitral regurgitation does not affect the accuracy of the new technique (Figure 3).

It must be emphasized that in the present study the calculation of mitral regurgitant fractions by Doppler echocardiography was based upon the use of an amplitude-weighted, but not a power-weighted mean velocity. This appears more appropriate in light of the theoretical observation that in normal blood with a hematocrit level of about 45%, a nonrandom distribution of the erythrocytes is present, where the amplitude of the backscattered signal is proportional to the number of scattering particles within the blood stream.16 In experimental studies, a random distribution of the scatterers is prevalent at hematocrit levels below 8%. In this situation, the power of the received signal rather than its amplitude would be proportional to the number of scattering particles.15

A technical factor that affects the measurement of AWMV is adequate width of the continuous wave beam. Ideally, in AWMV measurements, a homogeneously interrogated ultrasonic field with a width of the continuous wave beam covering the whole...
area of the aortic or the mitral anulus, respectively, should be present at any instant of signal recording to assess true systolic or diastolic blood flow volumes. In fact, with the equipment used, the width of the continuous wave beam may often be less than the diameter of the anulus area investigated. This is especially true for the mitral anulus orifice, and as a consequence, it could result in an underestimation of the mitral regurgitant fraction. The results obtained in this study, however, show satisfying agreement with the reference method used.

Ultrasonic attenuation is approximately the same for the aortic and the mitral anulus because in both cases recordings are performed by placing the transducer in the apical window position. The mean difference in depth between aortic and mitral anulus being 0.5 cm, the impact of this difference—caused by attenuation—is only 9%/cm depth range of the signal amplitude. Moreover, the use of the amplitude of the ultrasonic signal rather than its power markedly reduces the negative impact of ultrasonic attenuation on the assessment of blood flow volume rates. The determination of mitral regurgitant fraction with AWMV is limited to laminar flow and, therefore, is only applicable if pure mitral regurgitation is present. In concomitant mitral or aortic stenosis, separation of the erythrocytes from blood plasma occurs and falsely increases the signal amplitude recorded over the stenotic area. According to our experience, this phenomenon does not exert a major influence on the computation of mitral regurgitant fraction by means of AWMV in slight stenosis and did not affect our results here.

The method is further limited to the incompetence of one valve and does not allow the calculation of regurgitant volumes because the stroke volumes provided are not absolute but only relative ones.

It is concluded that the method described here to quantify mitral regurgitation from AWMV measurements is accurate and allows easy, noninvasive determination of the degree of valvular incompetence in clinically routine applications. This method is also theoretically valid in the case of pure aortic regurgitation. In contrast to conventional Doppler echocardiographic approaches, the method is independent of the need to measure the area of the left ventricular inflow and outflow tracts and the corresponding mean blood flow velocities.

References


**KEY WORDS** • amplitude-weighted mean velocity • mitral regurgitation • continuous wave Doppler
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