METHODS

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

HARALD HOPPELER, MD, ROLF JENNI, MD, MSEE, MANFRED RITTER, MD, HANS PETER KRAYENBUHL, MD

Zurich, Switzerland

Aortic regurgitant fraction (RFao) was quantified by estimating the ratio of the forward blood flow through the aortic (Qao) and pulmonary (Qp) valve: RFao =100(Qao - Qp)/Qao. Aortic and pulmonary flow were measured by the systolic time integrals of the amplitude-weighted mean velocity from continuous wave Doppler spectra recorded over the aortic and pulmonary valves. Thus, measurements are independent of the left and right ventricular outflow tract area.

In 20 normal subjects, aortic regurgitant fraction ranged between -2.9% and +12.0% (mean +4.3%), the physiologic value being +2%. In 20 patients with pure aortic regurgitation, aortic regurgitant fraction obtained by

Doppler spectra (y) was compared with that calculated from biplane left ventriculography and cardiac output determined with the Fick method (x). The correlation was r = 0.94, (SEE = 5.4%, which is 10.6% of the angiography-Fick mean value). The regression line was y = 0.87x + 6.6 (mean y = 51.2%, mean x = 51.1%).

It is concluded that determination of aortic regurgitant fraction in pure aortic regurgitation by using the amplitude-weighted mean velocity from continuous wave Doppler spectra is accurate and allows easy noninvasive evaluation of the regurgitant fraction in routine clinical applications.

(J Am Coll Cardiol 1990;15:1305-9)

During recent years, Doppler echocardiography has brought important advances in the assessment of valvular heart disease (1-4). Currently available Doppler methods for semiquantitative evaluation of aortic regurgitation include pulsed Doppler ultrasound mapping of the regurgitant jet (5,6), measurement of the reverse diastolic blood flow at different locations within the aorta (7,8) and Doppler color flow mapping (9,10). Pressure half-time calculation (11,12) became possible with continuous wave Doppler echocardiography.

Quantification of aortic regurgitation requires the determination of left ventricular total stroke volume, as well as forward stroke volume. Classically, these variables are obtained at cardiac catheterization from ventriculography combined with cardiac output estimated by indicator-dilution techniques or the Fick method (13). Conventional Doppler echocardiographic methods determine volumetric flow through valvular orifices (14,15) by pulsed Doppler velocity measurements within the orifice and calculation of its cross-sectional area from the two-dimensional echocardiographic image. For routine clinical applications, this approach has some limitations because the determination of accurate mean blood flow velocity within the cross-sectional area and the precise measurement of the corresponding cross-section prove to be critical and time-consuming.

This report presents a novel method for quantifying aortic regurgitation from the systolic time integrals of amplitude-weighted mean flow velocity from Doppler spectra recorded over the aortic and pulmonary valve in 20 healthy volunteers and 20 patients with various degrees of pure aortic regurgitation.

Methods

Theoretical considerations. In normal blood with a hematocrit of approximately 45% (16,17), the amplitude of the recorded Doppler signal is proportional to the number of scattering erythrocytes (18). The sum of the individual velocities of the erythrocytes recorded within the Doppler spectrum multiplied by the respective signal amplitude is
called amplitude-weighted mean velocity (AWMV) and is proportional to instantaneous blood flow:

\[ Q \sim \text{AWMV} = \int_{f_0}^{f_x} A(f)df, \quad [1] \]

where \( Q \) = flow rate, \( A(f) \) = amplitude of the spectral density, \( f = \) Doppler shift, \( f_x = \) spectral range and \( f_0 = \) cutoff frequency of the wall filter.

The time integral of the amplitude-weighted mean flow velocity is proportional to blood flow volume during a given time interval. For adequate assessment of blood flow volume rates in the quantification of aortic regurgitation, it is essential to sample all backscattered signals from the erythrocytes passing through the pulmonary or aortic orifice; this necessitates a homogeneous interrogation of the anulus area of interest by the continuous wave Doppler beam and, thus, adequate width of the continuous wave beam. Ideally, the amplitude-weighted mean velocity of a thin layer within the orifice of interest should be used to assess blood flow volume rates (16,17). This condition is obtained by low pass filtering, which confines the volume of interest to the fast-flowing scattering particles (that is, particles within the pulmonary or aortic anulus area) (16,17). The attenuation of the ultrasound waves with increasing distance from the transducer could theoretically bias the accuracy of the method for quantitating aortic regurgitation. Because the distances of the aortic and pulmonary anulus sites from the transducer often appreciably differ, an error inherent to the method must be considered.

**Equipment.** Ultrasound examinations were performed with a real time phased-array sector scanner (HP 77020, Hewlett Packard), equipped with a 2.5 MHz crystal transducer for imaging and a 1.9 MHz crystal set for continuous wave Doppler recording. The half maximal width of the continuous wave beam measured 13 mm at a distance of 10 cm from the transducer and 18 mm at a distance of 15 cm. Adaptation of the software was provided by the manufacturer (Hewlett Packard) to calculate amplitude-weighted mean velocity from equation 1.

**Recordings.** Patients were examined in the left lateral decubitus position. The apical window was used to measure blood flow through the aortic valve, and the pulmonary artery was imaged in the left parasternal view. The continuous wave Doppler beam was superimposed on the sector image and positioned along the axis of flow in such a way that spectra with the largest possible velocities were obtained. Recordings of both aortic and pulmonary flow were performed at identical gain settings. For low pass filtering, a filter of 200 Hz was used in all patients. The amplitude-weighted mean flow velocity was superimposed on the continuous wave spectrum and recorded together with the electrocardiogram on a Panasonic 6200 VHS video recorder. Figure 1 shows an example of Doppler recordings from the pulmonary artery and aorta. The systolic time integral of the amplitude-weighted mean velocity curve was planimetered over individual cardiac cycles by a track ball system. For further calculations, the four highest amplitude-weighted mean flow velocities were averaged.

**Study group and evaluation of the method.** Pulmonary (Qp) and aortic (Qao) flow rates were measured by Doppler echocardiography in 20 healthy volunteers aged 30 to 68 years. In the absence of valvular regurgitation or intracardiac shunting, blood flow through the aorta exceeds the pulmonary blood flow by about 2% (19), reflecting the
additional blood flow through the bronchial arteries. Aortic regurgitation (RFao [%]) was calculated as:

\[ RFao = 100 \left( \frac{Qao - Qp}{Qao} \right) \]

where Qao and Qp = aortic and pulmonary blood flow, respectively. In normal subjects, the theoretically expected value (19) is +2%. This determination of aortic and pulmonary blood flow permitted a direct evaluation of the method independent of any other method.

In 20 patients aged 33 to 76 years with various degrees of pure aortic regurgitation, aortic regurgitant fraction was determined as already described by Doppler echocardiography and compared with the angiography-Fick procedure. Mitral regurgitation was excluded by both angiography and Doppler echocardiography. Standard biplane left ventriculography was performed in all patients with aortic regurgitation in the right and left anterior oblique projections. End-systolic and end-diastolic volumes were determined by the area-length method (20). Forward cardiac output and stroke volume were calculated by the indirect Fick method. The regurgitant fraction was then calculated as 100 × (angiographic stroke volume - Fick stroke volume)/angiographic stroke volume.

**Statistical analyses.** For statistical analyses, the paired Student's t test and simple linear regression analysis were used.

**Results**

**Aortic regurgitant fraction in normal persons.** In the 20 normal persons, aortic regurgitant fraction calculated from the average amplitude-weighted mean flow velocity values in both great arteries ranged from −2.9% to +12.0% (mean ± SEM 4.25 ± 0.95%) (Fig. 2).

**Aortic regurgitant fraction in pure aortic regurgitation.** In the 20 patients with pure aortic regurgitation, there was a good correlation between the values of the aortic regurgitation fraction (RFao [y]) estimated by amplitude-weighted mean velocity Doppler echocardiography and the values of the aortic regurgitant fraction (RFao [x]) obtained by the angiography-Fick method (Table 1, Fig. 3). The correlation coefficient was 0.94, and SEE 5.4%, or 10.6% of the angiography-Fick mean value. The regression line was \( y = 0.87x + 6.6 \). The mean regurgitant fraction determined by amplitude-weighted mean velocity measurements was 51.2% (range 8% to 82%); the mean angiographically determined regurgitant fraction was 51.5% (range 5% to 83%).

**Discussion**

**Accuracy of the method.** We have presented a novel method to quantify aortic regurgitation with amplitude-weighted mean flow velocity from continuous wave Doppler spectra. We tested the method in 20 normal persons without valvular regurgitation. Physiologically, the relative difference between aortic and pulmonary blood flow volume is known to be +2%, which accounts for the additional blood flow through the bronchial arteries. The range of −2.9% to +12.0% indicates the scatter of the Doppler method. The mean value of +4.3% and the SEM are indicated by solid bars. Qao and Qp = aortic and pulmonary blood flow, respectively.
Table 1. Doppler and Angiography-Fick Data in 20 Patients With Aortic Regurgitation

<table>
<thead>
<tr>
<th>Patient No.</th>
<th>Age (yr)/ Gender</th>
<th>Diagnosis</th>
<th>Rhythm/ Blood Pressure</th>
<th>Doppler</th>
<th>Angiography Fick (catheterization)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Heart Rate/ RFao (%)</td>
<td></td>
<td>Systolic/Diastolic RFao (%)</td>
</tr>
<tr>
<td>1</td>
<td>50/M</td>
<td>CAD, AR</td>
<td>84/63</td>
<td>130/50</td>
<td>117/48</td>
</tr>
<tr>
<td>2</td>
<td>54/M</td>
<td>AE, AR</td>
<td>78/60</td>
<td>155/60</td>
<td>119/56</td>
</tr>
<tr>
<td>3</td>
<td>68/M</td>
<td>AE, AR</td>
<td>84/60</td>
<td>150/85</td>
<td>128/51</td>
</tr>
<tr>
<td>4</td>
<td>67/M</td>
<td>AE, AR</td>
<td>74/50</td>
<td>140/50</td>
<td>169/58</td>
</tr>
<tr>
<td>5</td>
<td>56/M</td>
<td>AR</td>
<td>86/117</td>
<td>160/95</td>
<td>149/81</td>
</tr>
<tr>
<td>6</td>
<td>54/M</td>
<td>AE, AR</td>
<td>62/60</td>
<td>170/40</td>
<td>159/56</td>
</tr>
<tr>
<td>7</td>
<td>62/M</td>
<td>AR</td>
<td>77/52</td>
<td>130/50</td>
<td>121/53</td>
</tr>
<tr>
<td>8</td>
<td>63/M</td>
<td>AE, AR</td>
<td>64/48</td>
<td>150/60</td>
<td>138/54</td>
</tr>
<tr>
<td>9</td>
<td>76/M</td>
<td>Endoc, AR</td>
<td>60/60</td>
<td>140/60</td>
<td>154/70</td>
</tr>
<tr>
<td>10</td>
<td>33/M</td>
<td>AR</td>
<td>63/41</td>
<td>130/70</td>
<td>136/68</td>
</tr>
<tr>
<td>11</td>
<td>48/M</td>
<td>CAD, AR</td>
<td>75/25</td>
<td>150/90</td>
<td>162/94</td>
</tr>
<tr>
<td>12</td>
<td>38/M</td>
<td>AR</td>
<td>56/52</td>
<td>140/60</td>
<td>132/53</td>
</tr>
<tr>
<td>13</td>
<td>47/F</td>
<td>AR</td>
<td>67/44</td>
<td>130/55</td>
<td>127/51</td>
</tr>
<tr>
<td>14</td>
<td>42/M</td>
<td>AR</td>
<td>60/56</td>
<td>155/60</td>
<td>146/58</td>
</tr>
<tr>
<td>15</td>
<td>64/M</td>
<td>AE, AR</td>
<td>54/51</td>
<td>160/95</td>
<td>166/82</td>
</tr>
<tr>
<td>16</td>
<td>66/M</td>
<td>AR</td>
<td>75/60</td>
<td>155/75</td>
<td>140/62</td>
</tr>
<tr>
<td>17</td>
<td>56/M</td>
<td>AR</td>
<td>68/40</td>
<td>125/75</td>
<td>104/67</td>
</tr>
<tr>
<td>18</td>
<td>56/M</td>
<td>AE, AR</td>
<td>65/46</td>
<td>120/70</td>
<td>105/45</td>
</tr>
<tr>
<td>19</td>
<td>35/M</td>
<td>Bicuspid, AR</td>
<td>85/65</td>
<td>140/55</td>
<td>120/50</td>
</tr>
<tr>
<td>20</td>
<td>45/M</td>
<td>Bicuspid, AR</td>
<td>53/82</td>
<td>130/65</td>
<td>142/55</td>
</tr>
<tr>
<td>Mean</td>
<td>51</td>
<td></td>
<td>66/47</td>
<td>130/60</td>
<td>124/55</td>
</tr>
<tr>
<td>±SD</td>
<td>16</td>
<td></td>
<td>11/21</td>
<td>43/24</td>
<td>43/21</td>
</tr>
</tbody>
</table>

AE = anuloectasia; AF = atrial fibrillation; AR = aortic regurgitation; Bicuspid = bicuspid aortic valve; CAD = coronary artery disease; Endoc = endocarditis; F = female; M = male; RFao = aortic regurgitant fraction determined by amplitude-weighted mean velocity or invasively by the angiography-Fick method; SR = sinus rhythm.

Theoretical considerations and limitations of the method.

Some technical factors need to be considered because they might influence the accuracy of the method. The ultrasound beam of the continuous wave Doppler transducer should be wide enough to include the whole area of the aortic or pulmonary anulus. Ideally, the anulus area of interest should be in a homogeneously interrogated ultrasound field at any instant of signal recording to assess true systolic blood flow volume rates. 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. In the presence of anulus diameters of about equal size, a possible underestimation of blood flow through one valve might be partly counterbalanced by the same error occurring at the other valve. The results obtained in this study show satisfying agreement with the reference method used. However, in the case of a severely dilated aortic anulus, a significant signal loss and underestimation of the regurgitant fraction might occur.

The aorta and pulmonary artery are examined from different transducer positions, and the distances from the transducer to the aortic and pulmonary valve are not always equal. Ultrasonic attenuation increases considerably with increasing distance from the transducer and amounts to about 9% per cm depth range (21). Nevertheless, with a
mean deviation of +2.3% from the expected "physiologic" value of 2% and an SEM of 0.95%, the results of the study sufficiently validate the applicability of the method.

Clinical limitations. The use of the amplitude-weighted mean flow velocity as described in this report provides a relative measure of stroke volume and thus does not allow the calculation of absolute regurgitant volume. It is further limited to the incompetence of one valve, and is only applicable in the presence of laminar flow (that is, in pure aortic regurgitation). In concomitant aortic or pulmonary stenosis, the high blood flow velocities occurring at the valve orifice will result in separation of the erythrocytes from blood plasma and falsely increase the signal amplitude (22,23).

Conclusions. The Doppler method described to quantify pure aortic regurgitation is accurate and allows easy noninvasive determination of aortic regurgitant fraction in routine clinical applications.

References