Doppler flow mapping and its comparison with the continuity equation method for quantifying aortic stenosis

D. KALMANSON*, C. VEYRAT†, C. GOURTCHIGLOUAN*, W. EL YAFI*, D. SAINTE BEUVE*

Fondation A. de Rothschild, Paris, France

KEY WORDS: Aortic stenosis, aortic valvular area, continuity equation, flow mapping, Doppler, ultrasound.

The flow-mapping technique, which detects and planimeters the area of systolic flow at the site of the aortic orifice, was applied to 29 patients with a stenosed aortic valve, all of whom underwent cardiac catheterization. The success rate was 93%. The correlation coefficient between the values of valvular areas obtained by Doppler and those yielded by the Gorlin formula was \( r = 0.93 \) (\( \text{SEE} = 0.12 \text{ cm}^2 \)). The continuity equation procedure, with the use of the velocity–time integrals, was applied sequentially to 20 of the above mentioned patients. The success rate was 85%. The valvular areas obtained in these patients by the Gorlin formula correlated well with those obtained with flow mapping \( (r = 0.90, \text{SEE} = 0.14, \text{ standard deviation of the difference} = 0.13 \text{ cm}^2) \), as well as with those yielded by the continuity equation procedure \( (r = 0.86, \text{SEE} = 0.17 \text{ cm}^2, \text{ standard deviation of the difference} = 0.16 \text{ cm}^2) \). Furthermore, the data from both ultrasonic methods were satisfactorily cross-correlated \( (r = 0.92, \text{SEE} = 0.12 \text{ cm}^2) \). It is noteworthy that the values of aortic valvular area obtained by Doppler were slightly larger than those found using either the continuity equation procedure or the Gorlin formula.

The authors conclude that the flow-mapping technique represents a reliable method for quantifying stenotic aortic valvular area and correlates well with the continuity equation procedure. It is therefore suggested that, whenever possible, both techniques should be used sequentially as a valuable and practical cross-checking policy.

At the present time, non-invasive assessment of the severity of aortic stenosis indubitably relies on Doppler data, because of failure of previous ultrasonic methods, such as echocardiography, to provide direct and specific data[1]. The Doppler techniques offer several ways of quantification. One relies on the pulsed Doppler flow mapping procedure: this acts as an internal microphone detecting all points of flow across the aortic valvular area, in the same way as has been already proposed for regurgitant aortic jets[2]. Another method combines flow measurements from pulsed and continuous-wave Doppler and relies on the continuity equation which uses the peak velocity, or a closely derived calculation using the time velocity integral[3,4]. In this report, we compared the results obtained from both non-invasive procedures on 20 patients of a group undergoing flow-mapping measurement of the stenotic jet.

Material and methods

STUDY POPULATION

The study population comprised 59 patients, consisting of 30 women and 29 men (mean age 59 years) undergoing left heart cardiac catheterization for aortic stenosis. Except for three patients in atrial fibrillation, all patients were in sinus rhythm. The aetiologies were rheumatic (14), degenerative with calcifications (43) and congenital (2). The associated lesions were minimal (10) or moderate (6) aortic regurgitation, mitral regurgitation (2), mitral stenosis (8) or prosthesis (2), tricuspid regurgitation (9), cardiomyopathy (2) coronary heart disease (6),

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and angiodysplasia (1). Thirty-six patients underwent surgical valvular replacement, and one had an aortic valvuloplasty.

**DIAGNOSIS**

The diagnosis of aortic stenosis was proven in all cases by invasive procedures including right and left catheterization with calculation of the aortic valvular area according to the Gorlin formula(9). Any important aortic regurgitation was ruled out by supravalvular aortography performed in the right anterior oblique position. Cardiac output was measured using either the Fick method or thermodilution, taking the average value from three measurements. Catheterization was performed within eight days of the Doppler examination, except for 10 patients for whom it was performed within a three-week period, and for one patient (at a one-year interval) in whom the clinical state remained unchanged.

**DOPPLER EXAMINATION**

Either a 3-MHz ATL 851 (35 patients), an Ultramark 8 (15 patients) or both (9 patients) (Scientific Medical system, Bellevue, WA, U.S.A.) mechanical real-time scanners were used providing a 90° sector and a single-gate steerable pulsed Doppler capability. The Doppler output could be represented as an audible signal and as a graphic display using fast Fourier transform spectral analysis at 5-ms intervals in all cases. Recordings were made on videotape, polaroid films, and/or on a Tektronics 4633.

**RECORDING TECHNIQUE**

The patients were generally studied in the supine left lateral position, according to a previously reported method(8).
**Pulsed Doppler flow-mapping procedure**

This procedure was applied to all patients. The parasternal short axis plane was used at the level of the aortic orifice, in order to obtain its entire visualization (Fig. 1). Once the cusps or parts of their tips had been visualized, the image was frozen in systole and the examiner looked for the presence of a Doppler signal with the following characteristics: its maximum amplitude, whether positive, negative or both, and duration had to occur before end-systole contemporary with the period of the aortic left ventricular pressure gradient (Fig. 2). Once this signal was detected, a to-and-fro mapping was performed from the centre to the boundary edges along the transverse, anteroposterior and oblique axes in order to delineate the limits of the area where it was heard. On review of videotapes this area was further planimetered with a Hewlett Packard integrator 98134 A with 1% error estimated from planimetry of test areas. The location of the stenotic area with regard to the entire aortic annulus was also noted. In order to check that the examination was performed at the level of the required plane, the length of the anteroposterior diameter measured in the short axis was always compared with that measured at the tips of the cusps in the long axis.

**Method derived from the continuity equation (Fig. 3)**

This method was applied to 20 of the 59 patients, in addition to the flow-mapping procedure.

(a) **Echocardiographic measurement of the reference diameter.** The left ventricular outflow tract was examined in the parasternal long-axis view$^{(3)}$ and the reference diameter was measured just below the insertion of the aortic cusps, freezing the image in early to mid-systole, depending on the timing of best visualization. The distance between the inner edges was measured using two internal calipers.

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**Figure 3.** Aortic stenosis: method derived from the continuity equation principle. (A) Measurement of the subvalvular diameter at the upper part of the outflow tract seen in long-axis view (inner to inner edges). (B) Pulsed Doppler recording of subvalvular velocities from the apex. (C) Continuous-wave Doppler recording of the velocities of the aortic jet, here obtained from the anterior axillary line. In systole, the darker part of the spectrum near to the zero line corresponds to the subvalvular velocities. (Severe stenosis, patient Bo. 15. average value 0.56 cm².) Mx maximum; m, mean; pr.gr, pressure gradient; other abbreviations as in Figs 1 and 2.
retaining the average value from three repeated measurements. These data were integrated as a cross-sectional area according to: $\frac{\pi D^2}{4}$.

(b) Doppler measurement. This method combined a pulsed Doppler recording of the left ventricular outflow tract velocities with a continuous-wave Doppler recording of the velocity of the aortic jet. The left ventricular outflow tract velocities were recorded from the apex (four- or five-chamber view) using two-dimensional Doppler. The main direction of flow was rapidly detected by mapping the width and length of the upper part of the outflow tract. The best signal with the highest velocities below the starting point of the jet was retained for analysis. The velocity traces, recorded at 50 or 100 mm $s^{-1}$, were digitized along the external contour in order to obtain the subvalvular time-velocity integral, averaging the value over three or five (patients with atrial fibrillation) successive beats.

The velocities of the aortic jet were recorded with a 2-25-MHz built-in non-imaging probe joined to the Ultramark 8 device, from the apical (12), suprasternal (4), left parasternal (2) and subcostal (2) approaches. When recordings had been obtained from several approaches, the one showing the highest velocities and the best contour was finally retained. Curves showing velocities opposite to the direction of the jet, or showing an insufficiently continuous and clear-cut contour were disregarded. The lower part of the curve generally showed a darker area corresponding to the subvalvular velocities, and it was always checked that they were of the same order of magnitude as those recorded previously with pulsed Doppler. The area under the velocity curve corresponding to the time-velocity integral of the aortic jet was digitized in the same way as for subvalvular curves. The assumption of an adequate alignment between flow and the ultrasonic beam relied on the best quality of the audiosignal generally obtained with minimal angulations of the transducer; no correction for the angle was made for any of these curves.

Calculations

The following calculation was made according to a previously reported procedure derived from the continuity equation: $AVA = (SubvA \times TVI) / TVI_{jet}$, where $AVA$ is the aortic valvular area, $SubvA$ is the subvalvular area, and $TVI$ is the time velocity integral of the subvalvular curve and the jet ($TVI_{jet}$).

**STATISTICAL STUDY**

All the non-invasive examinations were performed independently from the results of catheterization carried out by separate teams.

**Inter- and intra-observer variability**

For flow mapping, inter- and intra-observer differences have been shown to be non-significant with correlational linear coefficients of 0.95 and 0.96, respectively. For the Doppler method derived from the continuity equation, variability was tested over eight patients, with correlational study using linear regression equations (Table 1).

**Aortic valvular areas**

For our definition of critical stenosis at catheterization, a value of $\leq 0.75$ cm$^2$ was retained. Values obtained for the aortic valvular areas from the flow-mapping procedure were compared with those obtained from the Gorlin formula using a linear-regression analysis with use of a least-squares method. The same analysis was also applied to the 20 patients who were examined by both non-invasive procedures: differences between measurements were studied using paired samples with determination of the mean, standard deviation and error of the mean, limits of agreement, and 95% confidence intervals.

<table>
<thead>
<tr>
<th></th>
<th>Linear correlation coefficient ($r$)</th>
<th>SEE</th>
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<tbody>
<tr>
<td></td>
<td>Intra-observer</td>
<td>Inter-observer</td>
</tr>
<tr>
<td>Subvalvular diameter</td>
<td>0.94</td>
<td>0.92</td>
</tr>
<tr>
<td>Subvalvular velocities</td>
<td>0.95</td>
<td>0.92</td>
</tr>
<tr>
<td>Aortic jet velocities</td>
<td>0.99</td>
<td>0.97</td>
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</table>
FLOW-MAPPING PROCEDURE

This procedure was applicable to 55 out of 59 patients, because of poor quality of the audio-
signal in four patients. Figure 4 shows the results of the correlative study between invasive and non-
invasive measurements. The linear regression
equation was $Y = 0.95x - 0.05$ ($r = 0.93$, $\text{SEE} = 0.12 \text{cm}^2$, $P < 0.001$). There was one error in the
classification of the stenoses (1.8%). The stenotic
areas were central (25) or eccentric (30). They were
rounded (30), ovoid with major anteroposterior (6)
or transverse (9) axis, and more rarely triangular (4)
or transverse slit-shaped (6). Surgery confirmed the
Doppler prediction of a central (8) and eccentric (4)
area, and found Monckeberg disease in 3 patients
with slit-like areas. No correlation was available for
the other patients operated on, because of con-
spicuous calcification.

METHOD DERIVED FROM THE CONTINUITY EQUATION

This method was applicable to 17 of 20 patients
(85%), because of failure to record a curve fulfilling
our methodologic requirements (2 patients) and
failure to measure the subvalvular diameter (1
patient). Table 2 shows the comparative invasive
and non-invasive measurements for the 17 patients
who had both procedures, together with the mean
values, standard deviations, mean differences
between measurements with standard deviation,
and error of the means. The limits of agreement
ranged from $-0.30$ to $+0.32 \text{ cm}^2$ (95% confidence
interval from $-0.37$ to $+0.41 \text{ cm}^2$) for the con-
tinuity equation method, and from $-0.19$ to
$+0.31 \text{ cm}^2$ (95% confidence interval from $-0.25$ to
$+0.37 \text{ cm}^2$) for the flow-mapping procedure. The
linear-regression equations were $Y = 1.04x - 0.05$
($r = 0.86$, $\text{SEE} = 0.17 \text{ cm}^2$) for the continuity
equation method, and $Y = 1.00x - 0.007$ ($r = 0.90$,
$\text{SEE} = 0.14 \text{ cm}^2$) for the flow-mapping procedure.
For both non-invasive procedures, the equation was
$Y = 0.99x + 0.06$ ($r = 0.90$, $\text{SEE} = 0.12 \text{ cm}^2$) (Fig.
5). In this particular group, there were three errors
in classification for the continuity equation method
(17.6%), and one error for the flow-mapping
technique (5.8%).
Table 2  Aortic valvular area (AVA) obtained at Doppler (flow mapping, continuity equation) and from catheterization

<table>
<thead>
<tr>
<th>No patients (n)</th>
<th>AVA Doppler (cm²)</th>
<th>AVA catheterization (Gorlin) (cm²)</th>
</tr>
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<tbody>
<tr>
<td></td>
<td>Flow mapping</td>
<td>Continuity equation</td>
</tr>
<tr>
<td>1</td>
<td>0.99</td>
<td>1.09</td>
</tr>
<tr>
<td>2</td>
<td>0.55</td>
<td>0.51</td>
</tr>
<tr>
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<tr>
<td>4</td>
<td>0.64</td>
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</tr>
<tr>
<td>5</td>
<td>0.77</td>
<td>0.78</td>
</tr>
<tr>
<td>6</td>
<td>0.60</td>
<td>0.65</td>
</tr>
<tr>
<td>7</td>
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<td>0.50</td>
</tr>
<tr>
<td>8</td>
<td>1.30</td>
<td>1.15</td>
</tr>
<tr>
<td>9</td>
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<td>1.20</td>
</tr>
<tr>
<td>10</td>
<td>1.01</td>
<td>1.07</td>
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<td>1.10</td>
<td>1.07</td>
</tr>
<tr>
<td>12</td>
<td>0.80</td>
<td>0.60</td>
</tr>
<tr>
<td>13</td>
<td>0.77</td>
<td>0.85</td>
</tr>
<tr>
<td>14</td>
<td>1.10</td>
<td>1.00</td>
</tr>
<tr>
<td>15</td>
<td>0.60</td>
<td>0.56</td>
</tr>
<tr>
<td>16</td>
<td>1.50</td>
<td>1.20</td>
</tr>
<tr>
<td>17</td>
<td>0.76</td>
<td>0.77</td>
</tr>
</tbody>
</table>

Mean value ± S.D.

|               | 0.89 ± 0.28       | 0.84 ± 0.25                     | 0.83 ± 0.31 |

Difference mean

|               | -0.00 ± 0.05      | 0.06 ± 0.12                     | 0.01 ± 0.16 |

Standard error

|               | 0.03 ± 0.03       | 0.03 ± 0.06                     | 0.04 ± 0.04 |

Discussion

At the present time, non-invasive procedures for providing a measurement of the valvular area in cases of aortic stenosis clearly supersede all previous methods, including the pressure-gradient method which has the shortcoming of being cardiac-output dependent. The reference method commonly used is the Gorlin formula, although some possible limitations might penalize its comparison with any new non-invasive method. These limitations are well known in cases of significant associated regurgitation. Inaccuracies may also occur over large areas when the pressure drop is small, and/or stem from errors in the measurement of cardiac output which is integrated into the formula. As for the discharge coefficient, it may not apply uniformly to all anatomical or clinical situations, and this point has been particularly stressed in the case of long, irregular stenoses with low cardiac output[9]. Nevertheless, the Gorlin formula is still widely accepted as a valuable reference, and its non-invasive approximation was recently attempted from Doppler measurements in children[10], and in adults with combination of an invasive cardiac-output determination[11]. In addition to these attempts derived from the Gorlin formula, the Doppler technique offers two different ways to measure the aortic valvular area without integrating the discharge coefficient. One method uses the flow-mapping procedure, where the Doppler gate acts as an internal microphone for detecting flow disturbances. This study shows that this procedure is quite pertinent for singling out critical areas requiring surgery; 96% of patients were adequately classified using the method. However, areas measured with Doppler were generally larger than those obtained from catheterization. This fact might partly be explained by the differences in nature between the Gorlin formula, which produces an average figure per unit of time and takes into account the contraction coefficient of the jet after its starting point, and flow mapping, which detects instantaneous flow passing through an anatomical lesion at the period of maximal flow. The differences might also stem from insufficient spatial resolution which affects the accuracy of determining absence of flow at the borders of the area. This factor[9], is likely to account for some of the variability observed between the Gorlin and Doppler data, particularly for small areas. The second method for estimating aortic valve area relies on the continuity equation principle which states that (velocity) × (cross-section) is a constant product; the aortic valve area may be obtained by dividing this product calculated at a reference area by the velocity of the jet. We chose to use the time–velocity integral rather than the peak velocity, because of frequently associated regurgitation in our study, which could give rise to errors related to a large transient pressure gradient without a significant stenosis which is sometimes encountered in such patients. The results of the present study suggested that measurement of the subvalvular diameter was the main source of variability, and, therefore, the inner edges were used for distance measurements as they are easier to define[4].

Comparison between the non-invasive procedures

The finding that areas obtained by flow-mapping are larger than those obtained with the continuity equation method is not surprising because: (i) the basic principles of the procedures are different; and (ii) calculation using the time–velocity integral is likely to estimate the effective area[3], the value of which is closer to that obtained using the Gorlin formula. Despite the apparent advantage of flow
mapping over the continuity equation procedure, both in terms of the rate of applicability and the correlation coefficient, it is still perhaps premature to draw a definitive conclusion, in part because of our longer experience in flow mapping and also because of the limited number of patients who underwent both techniques. Nevertheless, when a new method is assessed, it seems more informative to examine the standard error of the estimate, and also to calculate the bias, estimated by the mean and the standard deviation of the differences, which determines the limits of agreement between methods\textsuperscript{[12]}. The best clinically acceptable method is the one that yields the narrowest limits and, consequently, the narrowest 95% confidence interval. In this regard, the variability in measurement by flow mapping, even if not ideal, was less important than that of the continuity equation procedure in our study. This might explain the lower rate of errors in classification using the flow-mapping procedure (1 vs. 3 errors) which, therefore, appeared more pertinent to clinical application. Further information is obtained by the flow-mapping procedure: it detects and quantifies aortic regurgitation in a single examination. Association with a subvalvular stenosis, not yet encountered, should not, theoretically, entail limitations. Flow mapping is the only procedure which gives information on the shape and site of the stenotic area, information which might be of increasing interest with the development of valvuloplasty. The time required for performing flow mapping (approximately 10 min) is quite competitive with that required for performing the three delicate measurements of the continuity equation method: velocity of the jet, subvalvular velocities, and diameter.

In conclusion, both procedures provide an estimation of the aortic valve area of a similar reliability. The combination of these methods should enhance the confidence in accurate results: we have seen that they show a satisfactory correlation, and any discrepancy between them raises doubt in one of them and calls for further checking of measurements. In addition, either method can be used as an alternative to the other in the rare cases of inapplicability of one of them.
This work was partly supported by grants from CNAMTS and from ARNTIC.

References