Quantitation of Aortic Insufficiency Using a Catheter-tip Velocity Transducer

Wilmer W. Nichols, Ph.D., Carl J. Pepine, M.D., C. Richard Conti, M.D., L. G. Christie, M.D., and R. L. Feldman, M.D.

SUMMARY Bidirectional instantaneous aortic root blood flow was measured in 18 patients with aortic insufficiency (AI) using a catheter-tip velocity transducer. The magnitude of AI was quantified by determining total forward systolic flow from the area of the flow velocity curve above the zero baseline and regurgitant diastolic flow from the curve area below the baseline. Effective forward flow (stroke volume) was calculated as the difference between total forward systolic flow and regurgitant diastolic flow. Regurgitant fraction was determined as the ratio of regurgitant flow to total forward flow. These data were compared with conventional angiographic estimates (1+ to 4+) of the degree of insufficiency. Velocity transducer determination of regurgitant fraction was 26% in the patient with 1+ AI, 37% (31–48%) in 2+ AI, 49% (35–61%) in 3+ AI and 72% in 4+ AI (regurgitant fraction vs angiographic grade, r = 0.84). Regurgitant flow per diastole was 9 ml in the patient with 1+ AI, 39 ml (20–49 ml) in 2+ AI, 57 ml (31–102 ml) in 3+ AI and 183 ml (143 and 223 ml) in 4+ AI (regurgitant diastolic flow vs angiographic grade, r = 0.73). Good correlation (r = 0.90) was found between values of regurgitant flow obtained from the left ventriculogram and those obtained using the velocity transducer.

Although the overall association was good, wide variability in regurgitant fraction and regurgitant flow was found in the 15 patients with 2+ to 3+ AI. These results suggest that the electromagnetic velocity catheter offers a simple technique for quantitating AI.

THE QUANTITY of blood flow that regurgitates across an incompetent aortic valve is determined by the cross-sectional area of the valve leaflet defect, the diastolic aortic-ventricular pressure gradient, and the duration of diastole. Although these determinants of the magnitude of aortic insufficiency (AI) have been appreciated since 1832,1 an accurate method to determine directly the magnitude of AI in awake man has not been generally accepted. Some methods proposed for quantitating the amount of AI include indicator dilution,2,3 left ventricular angiocardiography,4,5 isotope techniques,6,7 magnetic flowmeters,8,9 and catheter-tip10 and transcutaneous bidirectional Doppler techniques.11 A commonly used technique to assess the severity of AI is supravalvar cineangiography.12,13 This method requires subjective visual estimation of the degree of opacification of blood in the aortic root compared with blood that flows retrograde across the aortic valve and opacifies the left ventricular cavity. Predicted severity of AI using angiography may differ appreciably from that found at surgery.14 This observation was verified by comparison of the cineangiographic grade of AI to the volume of blood flowing retrograde across the valve measured with a perivascular electromagnetic flow probe placed around the ascending aorta during surgery.15 Advances in design have made it possible to place an electromagnetic flow probe at the tip of a cardiac catheter that can be inserted into a peripheral vessel and advanced to the site where the flow is to be measured.16 As a result, pulsatile blood flow velocity wave forms can be recorded from the ascending aorta during catheterization. From this wave form and the diameter of the aorta, the regurgitant flow volume can be determined. This technique has been used for the aorta17 and pulmonary artery18 of dogs. Recently, its application to the pulmonary artery of children with pulmonic insufficiency has been described.19 In the present investigation, we used an electromagnetic catheter-tip velocity transducer to measure bidirectional pulsatile aortic root blood flow in patients with aortic valve insufficiency. Both regurgitant and effective forward flow and regurgitant fraction were determined and compared with the supravalvar cineangiographic estimate of AI. Regurgitant flow was also compared with estimates obtained from single-plane left ventricular angiograms (total forward stroke volume) and dye dilution (effective stroke volume).

Methods

Patient Selection

We studied 18 adult patients undergoing cardiac catheterization to evaluate clinical findings due to valvular heart disease. Informed consent was obtained from each patient. Twelve of these patients had no clinical evidence for involvement of other valves and six had coexistent valve lesions (table 1). All patients were in sinus rhythm.

Cardiac Catheterization Studies

Catheterization was performed from a right antecubital cutdown with the patient in a fasting, postabsorptive state without premedication. A #7F Cour-

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determination was obtained in each patient by the indicator-dilution technique. Indocyanine green dye was injected into the right atrium, with pulmonary artery sampling. Duplicate cardiac output determinations in our laboratory vary ± 5%.

Phasic velocity of aortic blood flow was measured with an electromagnetic catheter-tip velocity transducer. The use of this catheter in our laboratory has been described in detail elsewhere.7 Before insertion, the distal part of the catheter, including the velocity and pressure transducers, was submerged in saline solution for several minutes. An in vitro zero-velocity signal was recorded. In each case this in vitro zero signal was the same as the electrical zero obtained by switching off the magnetic current (fig. 1). The velocity catheter was then inserted through a brachial arteriotomy and positioned in the ascending aorta at the level of the aortic sinuses. After recordings were made, the catheter was withdrawn until the velocity sensor was in the brachial artery. With the sensor within the artery the vessel was totally occluded by a snare of umbilical tape positioned proximal to the tip to establish an in-vivo hydraulic zero (fig. 1), and recordings were made.

The velocity catheter was replaced with a #8F NIH catheter. Aortic root angiography was performed using standard cine technique in the left anterior oblique projection. The catheter was then advanced to the left ventricle. Left ventriculography was performed in the right anterior oblique projection. The angiograms were calibrated by reference to a grid.

Recordings, Measurements and Calculations

When all catheters were in position, recordings of aortic blood flow velocity and pressure and a standard electrocardiographic lead were made simultaneously at slow and fast (200 mm/sec) paper speeds on a multichannel recorder (Electronics for Medicine). The area under the aortic blood flow velocity wave form above the zero baseline was determined by planimetry from recordings at 200 mm/sec. The product of this area and aortic cross-sectional area was taken to represent total forward flow (ml). Regurgitant flow (ml) was calculated similarly using the area below the zero baseline (fig. 2). For each subject at least nine consecutive cardiac cycles were selected for measure-

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**Table 1. Pulsatile Hemodynamic Findings in Patients with Aortic Valve Insufficiency**

<table>
<thead>
<tr>
<th>Pt</th>
<th>Age (years) Diagnosis</th>
<th>Angio grade of AI</th>
<th>HR (beats/min)</th>
<th>LVEDP (mm Hg)</th>
<th>Aortic pressure (mm Hg)</th>
<th>Aortic radius</th>
<th>Forward SV</th>
<th>Effective SV</th>
<th>Regurgitant SV</th>
<th>RF (%)</th>
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<tr>
<td>1</td>
<td>22 AI</td>
<td>2</td>
<td>124</td>
<td>10</td>
<td>141 174 100 1.5</td>
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<td>45</td>
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<td>2</td>
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<td>23</td>
<td>112 170 70 1.6</td>
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<td>68</td>
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<td>22</td>
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<td>75</td>
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<td>107</td>
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*Starr-Edwards aortic prosthesis.

Abbreviations: AI = aortic insufficiency; HR = heart rate; SV = stroke volume; RF = regurgitant fraction; LVEDP = left ventricular end-diastolic pressure.
ment so that premature and immediately postpre-
mature beats were omitted. Mean values for both
forward and regurgitant flow per beat were deter-
mined. Regurgitant fraction was calculated as the
ratio of regurgitant flow per diastole and total forward
flow per systole \( \times 100\% \). Effective forward flow (ml)
was determined as the difference between total for-
ward flow per systole and regurgitant flow per diastole.

Aortic and left ventricular angiograms were
analyzed on the same Tago Arno projector. The grade
of AI was estimated from 1 to 4+ according to criteria
outlined by Cohn et al. Aortic root diameter was
measured as described elsewhere. All angiographic
analyses were done by the same observer to eliminate
interobserver variability. These analyses were done by
another observer before calculation of regurgitant
flow derived from velocity catheter recordings. Left
ventricular end-diastolic and end-systolic volumes
were calculated from the ventriculogram using the
single-plane method of Sandler and Dodge. No
patient had localized wall motion abnormalities.
Forward and regurgitant flow values were also
calculated from the angiographically derived stroke
distance and the stroke volume was determined from
the indicator-dilution cardiac output.

Results of catheter-tip velocity transducer
determinations of AI were compared with cineangi-
ographic magnitude of AI using a simple linear regres-
sion program.

Results

The results are summarized in tables 1 and 2. Cine-
angiographic degree of AI ranged from 1+ to 4+.
Catheter-tip velocity transducer determinations of
regurgitant volume flow per diastole and regurgitant
fraction ranged from 9–223 ml and 26–72%, respec-
tively. Examples of electromagnetic flowmeter record-
ings of bidirectional pulsatile blood flow obtained
from patients 5, 12, 13 and 15, who had different cine-
aortographic degrees of AI, are shown in figure 3.
These four patients had total forward stroke volumes
of 35 ml, 119 ml, 133 ml and 310 ml and regurgitant
flows per diastole of 9 ml, 44 ml, 58 ml and 223 ml,
respectively. Regurgitant fractions (and cine degrees)
were 26% (1+), 37% (2+), 45% (3+), and 72% (4+)
and effective stroke volumes were 26 ml, 75 ml, 75 ml
and 87 ml, respectively, for these four patients.

Velocity Catheter Determination of Regurgitant Fraction

Regurgitant fraction determinations were com-
pared with cineaorticographic grade of AI (fig. 4). Four
patients had mitral regurgitation in addition to AI.
The horizontal bar in the figure represents the mean
percentage of regurgitation for each cineangiographic
grade of AI. The only patient with 1+ AI had a
regurgitant fraction of 26%. The regurgitant fraction
ranged from 31–48% for the five patients with 2+ AI
and from 31–61% for the 10 patients with 3+ AI. The
two patients with 4+ AI had regurgitant fractions of
71% and 72%. Although mean values of regurgitant
fractions increased with the severity of AI (\( r = 0.84 \)),
the individual values overlapped considerably. For
example, five of 10 patients with 3+ AI had regurgitant
fractions within the range found for patients with 2+ AI.

Velocity Catheter Determination of Regurgitant Flow

The volume of blood regurgitated across the aortic
valve during diastole was calculated and plotted
against the cineangiographic grade of AI for each
patient (fig. 5). When measured regurgitation is
expressed as milliliters per diastole, a wide overlap
between patients with 2+ and 3+ angiographic AI
was found, although the mean regurgitant flow
increased for each grade (\( r = 0.73 \)). Patients with angi-
ographic 2+ AI had regurgitant flows of 20–49
FIGURE 3. Electromagnetic velocity catheter recordings of pulsatile blood flow in the ascending aorta of four patients with aortic regurgitation. Each cineangiographic grade (1+, 2+, 3+ and 4+) of aortic insufficiency (AI) is shown along with the corresponding regurgitant fractions (RF). Tracing A was recorded at a paper speed of 100 cm/sec and tracings B, C and D were recorded at 50 cm/sec.

ml/diastole and those with 3+ AI had regurgitant flows of 31–102 ml. The only patient with 1+ AI had a regurgitant volume of 9 ml/diastole and the two patients with 4+ AI had regurgitant volumes of 143 and 223 ml/diastole.

FIGURE 4. Catheter-tip electromagnetic velocity transducer determinations of percent total forward flow regurgitated compared with supravalvular cineangiographic grade of aortic insufficiency. The horizontal bars represent the mean values of the regurgitant fraction for each cineangiographic grade. Considerable crossover is seen in the data points, especially between grades 2+ and 3+.

FIGURE 5. Catheter-tip velocity transducer determinations of regurgitant flow per diastole compared with supravalvular cineangiographic grade of aortic insufficiency. The data points for patients with grades 2+ and 3+ aortic insufficiency overlap considerably.

Velocity Catheter Determination of Regurgitant Flow vs Angiographically Determined Regurgitant Flow

In patients 3–14, regurgitant flow per diastole was also obtained as the difference between total forward stroke volume (left ventriculography) and effective stroke volume (dye dilution). Good correlation ($r = 0.90$) was found between these values of regurgitant flow and values measured by velocity catheter (tables 1 and 2). In patients 1 and 2, acceptable ventriculograms were not obtained, and in patients 15–18, regurgitant flows could not be obtained due to the presence of mitral insufficiency.

Discussion

We recorded bidirectional pulsatile aortic root blood flow with a catheter-mounted electromagnetic blood velocity sensor in a group of patients with AI. Regurgitant flow per diastole and regurgitant fraction were measured and compared with subsequent cineangiography estimates of AI (figs. 4 and 5). Our results indicate that cineangiography can distinguish between mild and severe AI (i.e., small and large regurgitant fractions), but between these extremes the angiographic technique has limited quantitative value. There are several reasons for disagreement between the two methods. Angiographic interpretation can be influenced by rate of delivery and amount of contrast material, position of the catheter, size of the aortic mixing chamber, size of the ventricular mixing chamber and ability of the ventricle to empty regurgitated contrast material. These variables are compounded by subjective observer interpretations and interobserver variability.

Our results are similar to those reported by Mennel
et al., who used a perivascular electromagnetic flow probe placed around the ascending aorta at surgery. Other investigators have used cuff-type flow probes to quantitate the magnitude of regurgitant volume in patients with AI. Although such probes provide an accurate measure of regurgitant volume, they can only be applied in anesthetized open-chest patients. The latter conditions alter blood pressure, heart rate and other factors known to influence regurgitant volume, thereby limiting the possible usefulness of flow measurements made at surgery. Placement of a velocity sensor at the tip of a cardiac catheter makes it possible to measure bidirectional pulsatile blood flow velocity in awake man during cardiac catheterization. Because the velocity profile of blood flow in the ascending aorta is relatively flat, the product of velocity and cross-sectional area is volume of blood flow per unit time.

Although various indirect methods have been used to estimate the magnitude of aortic regurgitation in man, there is still need for a simple and accurate technique to assess AI. The technique used by Sandler et al. and Hunt et al. appears to be reliable for quantitating AI. With this method both the amount of blood regurgitated and regurgitant fraction are obtained by subtracting effective forward stroke volume from total volume ejected. Effective stroke volume is determined from cardiac output measured by indicator-dilution or Fick techniques. Total volume ejected is determined from the difference between end-systolic and end-diastolic volumes measured by ventriculography. Some limitations to this method are that alterations in ventricular geometry require both biplane angiography and numerous simplifying assumptions to determine left ventricular volumes. The necessity for angiography limits the number of determinations that can be made and makes determinations made during common arrhythmias, such as atrial fibrillation or premature ventricular complexes, open to error. Effects of radiographic contrast material on both ventricular and systemic hemodynamic function could alter the magnitude of regurgitation. Finally, the method is time-consuming and requires analysis well after the patient leaves the laboratory.

The most commonly used method of assessing the degree of AI is by supravalvular cineangiography. This simple but very subjective technique provides only a rough estimate of the degree of insufficiency. Data reported here and by others support this contention. Comparison of stroke volume obtained using the velocity catheter with stroke volume simultaneously obtained by dye dilution showed excellent correlation ($r = 0.93$, $y = 0.93x + 0.26$ l/min.) The velocity catheter technique is safe and easy to use for obtaining beat-to-beat stroke volume, and does not alter aortic and left ventricular pressure, which may influence the degree of AI. Regurgitant flow per diastole and effective flow per systole can be obtained rapidly either on-line, with a special analog computing circuit, or by simple planimetry, as in this study. The method is not influenced by other valve dysfunction, intracardiac shunts or ventricular geometry.

When arrhythmias such as atrial fibrillation are present, determinations can simply be averaged from a larger sample of cardiac cycles.

One important requirement to obtain accurate values of forward and retrograde flows, is precise determination of a zero-flow reference. Errors in zero baseline influence both forward and retrograde flow, but the changes are in opposite directions and would tend to yield large errors in calculated regurgitant fraction. In our studies, the hydraulic zero reference was set to match the electrical zero before catheter insertion. After measurements were made, the catheter was withdrawn until the velocity sensor was in the brachial artery. The vessel was totally occluded to establish an in vitro zero-flow reference (fig. 1). Zero baselines obtained using these techniques were, in most cases, the same. If deviation was noted, the hydraulic zero obtained during vessel occlusion was always used as the zero reference.

Another possible source of error is variation of aortic cross-sectional area during the cardiac cycle. In previous studies in 10 patients with normal aortic valves, changes in ascending aortic cross-section during ejection were estimated with an electrical strain-gauge caliper and found to be 11% of the diastolic value. Measurements of aortic cross section in patients with aortic insufficiency have not, to our knowledge, been reported. In our laboratory, however, measurements of aortic root cross-sectional area from high-speed angiograms in patients with AI showed changes throughout the cardiac cycle that averaged 12%. In calculation of volume flow per unit time, mean cross-sectional area was used to minimize this error.

Calculation of volume flow from velocity measurements assumes a flat velocity profile. Adequate data, however, are not available relative to diastolic velocity profiles in patients with aortic insufficiency. Schultz et al. and Tunstall-Pedoe presented a few examples in their studies on the diastolic profile in patients with AI. They found an essentially flat diastolic velocity profile. The systolic velocity profile was also flat in these patients. Using high-speed (90 frames/sec) cineangiograms, we found that patients in the present study had flat ascending aortic velocity profiles.

Accuracy of our measurements of forward and retrograde flow with the catheter-tip velocity transducer are difficult to evaluate because no reliable quantitative method is available for comparison. However, we did compare the regurgitant flow measured with the velocity catheter with those obtained from left ventricular cine angiograms and dye dilution. Good correlation was found between the two methods ($r = 0.90$). We also compared the effective forward stroke volumes measured with the velocity catheter to those obtained simultaneously using dye dilution and found good correlation between the two methods ($r = 0.84$, $y = 1.16x - 6.7$ ml). In dogs with chronic AI, Nolan et al. found a high correlation between regurgitant fractions obtained with an electromagnetic catheter-tip velocity transducer and those measured with a perivascular flow probe ($r = 0.91$,...
y = 1.11x + 0.51). Excellent correlations were also found for regurgitant volume and effective stroke volume.

In conclusion, we measured the magnitude of retrograde flow in AI in awake man using a catheter-tip velocity transducer. The technique provides a quantitative assessment of regurgitant blood flow in addition to effective forward flow and regurgitant fraction and is easy to use. These data may help determine the functional and prognostic significance of an incompetent aortic valve. Additionally, preliminary studies suggest that the techniques may help evaluate the effects of drug therapy designed to reduce the amount of regurgitation.26

References
Quantitation of aortic insufficiency using a catheter-tip velocity transducer.
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