Effects of Pressure and Volume of the Receiving Chamber on the Spatial Distribution of Regurgitant Jets as Imaged by Color Doppler Flow Mapping

An In Vitro Study

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Regurgitant jet dimensions imaged by color Doppler flow mapping have been used to evaluate the severity of valvular insufficiency in clinical studies. To study the effect of pressure and volume within the receiving chamber on the magnitude of spatial distribution of regurgitant jets assessed by color Doppler techniques, we designed a simple constant-flow model in which a jet was driven through a known orifice (1.5 mm²) into a compliant receiving chamber by a steady-flow pump. A distal tube at the outflow closed the system and maintained the volume of the chamber constant during pump operation. We varied flow rate from 60 to 270 ml/min into elastic balloons with different static compliances of 1, 2, 4.5, and 9 ml/mm Hg (pressures of 57, 28, 18, and 8 mm Hg, respectively); the balloons served as receiving chambers at the constant volume of 150 ml. We also evaluated the effect of different volumes of a receiving chamber (110, 130, and 150 ml and pressures of 5, 15, and 24 mm Hg) with a static compliance of 2 ml/mm Hg over the same range of flow rates. For each of the different balloons, jet area correlated linearly with the jet velocity across the orifice (r=0.98, 0.99, 0.98, and 0.97) and also with flow rate (r=0.97, 0.99, 0.98, and 0.99). At the same flow rate and volume of receiving chamber, however, the jet area imaged by color Doppler decreased as the pressure in the receiving chamber increased, although receiving-chamber volume was constant. In the balloon with static compliance of 2 ml/mm Hg and constant flow rate, the absolute color Doppler jet area decreased as both volume and pressure of the receiving chamber increased. Our results suggest that in a pulsatile system the pressure-volume relationship inside the receiving chamber may be a major determinant of regurgitant jet area as imaged by color Doppler. Even in a chamber with constant static compliance, changes in volume and pressure within the receiving chamber can result in significant changes in jet area independent of changes in driving pressure and regurgitant volume. (Circulation 1991;83:605–613)

The ability to accurately detect valvular regurgitation using spectral or color Doppler techniques has been an important application of cardiac ultrasound. Based on the rationale that the magnitude of flow disturbance in the receiving chamber could reflect the volume of regurgitation, these techniques, especially color Doppler, have been extensively used in the clinical setting to estimate the severity of regurgitation.1-12 Recently, however, an improved understanding of the interrelations between flow mapping and hydrodynamics has brought to light a number of important limitations in the grading of the severity of regurgitation by these techniques. Experimental studies13-16 have shown that physiological factors besides the volume of regurgitation can affect the magnitude of spatial distribution of turbulent jets, including the driving pressure and the area of the regurgitant orifice; a variety of technical factors related either to the instrumen-
regation27 were recorded by color Doppler techniques when the balloon viewing port was distally positioned in the receiving chamber. The ultrasound transducer was positioned at a balloon viewing port parallel to regurgitant flow coming toward the transducer.

The compliance was determined by analysis of the pressure–volume relation obtained by stepwise increases in the volume of the balloons while measuring chamber pressure using a simple water manometer; the results were converted to and expressed as millimeters of mercury (Figure 2). The pump study was performed using chamber volumes included in the linear portion of the pressure–volume curves for each chamber.

To study the effect of pressure on color Doppler regurgitant areas, we evaluated four elastic balloons with static compliances of 1, 2, 4.5, and 9 ml/mm Hg and pressures of 57, 28, 18, and 8 mm Hg, respectively, at a constant receiving-chamber volume of 150 ml. Flow rates varying from 60 to 270 ml/min were conducted into each receiving chamber by changing the output of the pump. In each experiment, the volume and pressure of the chamber were constant during pump operation. In addition, we analyzed the effects of receiving-chamber volumes of 110, 130, and 150 ml and corresponding pressures of 5, 15, and 24 mm Hg in a balloon with a constant static compliance.

Methods

Constant Flow Model

We simulated regurgitant jets under constant-flow conditions using a closed-flow system in which an electromagnetic steady-flow pump (model BC-3C-MD, March Manufacturing, Inc., Glenview, Ill.) was connected by distensible tubes and a needle 2–3 mm in length with known orifice area (1.5 mm²) to a compliant receiving chamber. Flow rates were varied by changing the knob of a variable direct current output transformer (Powerstat variable transformer, 120 V alternating current input, 0–140 V direct current output, Powerstat Inc., Bristol, Conn.) electrically connected to the pump. A distal tube at the outflow of this chamber maintained constant chamber volume during pump operation. A diagrammatic representation of the model is shown in Figure 1. The system was filled with a 1% cornstarch particle/water suspension to produce ultrasound reflections with physiological Doppler shift intensities.26 The design of the system permitted a rigid control of driving velocity and flow rate as well as of volume and ambient pressure of the receiving chamber.

To obtain different pressures at the same volume, a series of receiving chambers with different static compliances27 were prepared from latex balloons made of materials with slightly different elastic prop-

![Figure 1. Diagram of the constant flow model. Fluid is pumped through a needle with known orifice in an elastic receiving chamber and returned to the pump at the same rate from a tube distally positioned in the receiving chamber. The ultrasound transducer was positioned at a balloon viewing port parallel to regurgitant flow coming toward the transducer.](image-url)

![Figure 2. Graph showing pressure–volume relation in one of the balloons studied. The static compliance was calculated as the inverse of the slope of the linear regression analysis for the relation between pressure and volume of the receiving chamber in the phase in which a linear relation (filled circles) was observed. The calculated compliance for this specific balloon was 2 ml/mm Hg.](image-url)
(2 ml/mm Hg) over that range of volumes. At each constantly held balloon volume, equivalent values for flow rate over the range of 60 to 270 ml/min were studied. The peak velocities driving from this flow varied from 0.6 to 3.0 m/sec in both experiments, as determined by continuous-wave Doppler measurements obtained parallel to the jets.

**Color Doppler Flow Mapping Studies**

Color Doppler flow mapping studies were performed using a color Doppler ultrasonograph (model SSH65A, Toshiba, Tokyo) with a 3.75-MHz transducer; imaging was from a balloon-viewing window with flow from the needle directed toward and parallel to the phased array transducer. All images were obtained by scanning a single plane at constant gain and at a pulse repetition frequency of 4 kHz in the velocity-variance mode. The plane of imaging was adjusted to maximize the area of the turbulent flow stream. All images were recorded on 3/4-in. videotape for subsequent analysis.

To determine the maximal driving jet velocity across the orifice for each experiment and to estimate flow rate, continuous wave Doppler interrogation was also performed from the balloon-viewing port using both an Irex system IIIB with a 3.5/2.25-MHz phased array/continuous wave Doppler transducer and a Toshiba SSH65A with a 2.5/1.9-MHz transducer with the continuous wave spectra recorded on a strip chart recorder. Flow rates were calculated from the continuous wave Doppler velocities and the known orifice area and were cross-checked against the pump flow calibration that was obtained for each setting with a stop watch and graduated cylinder. The pump flow calibration measurement was considered the flow rate variable and was used for statistical analysis of results and for cross-checking our maximum velocity values.

**Image Analysis**

For each steady-flow state, we selected, from a frame-by-frame analysis of the videotape recordings, five images demonstrating visually the maximum jet distribution and the highest intensity of variance encoding. A color video-digitizing computer (model 70G, Sony Medical Systems) with an on-screen digitizing capability was used to measure the jet areas. Color jet areas were determined by tracing the boundaries of the contiguous color-encoded area of the jet (Figure 3). A mean area (±SD) of five selected images was computed for the different hydrodynamic conditions of the study for each receiving chamber volume or pressure evaluated. All measurements were made by two observers who were not aware of the corresponding experimental hydrodynamic conditions. The average of their measurements represented the final data set. There was close agreement between the two observers’ measurements ($r=0.998$, $y=0.96x+0.03$ cm$^2$, SEE=0.17 cm$^2$) and less than 3% difference between measured areas.

**Statistical Analysis**

Correlation analyses were performed using the Pearson correlation technique, and tests of statistical significance were performed by unpaired Student’s $t$ test and one-way analysis of variance with the level of significance set at $p<0.05$.

**Results**

**Effect of Flow Rate and Jet Velocity**

The simulated regurgitant jets imaged by color Doppler were highly reproducible under all flow conditions studied. For each different chamber pressure or volume evaluated, the spatial distribution of jets increased linearly with flow rate or with the driving velocities across the orifice. Figure 4 shows the relation between jet velocity and flow rate with jet area observed in a receiving chamber with a static compliance of 2 ml/mm Hg. For each of the individual receiving chamber static compliances of 1, 2, 4.5, and 9 ml/mm Hg, at pressures of 57, 28, 18, and 8 mm Hg, respectively, a strong correlation between jet area and jet velocity ($r=0.98$, $0.99$, $0.98$, and 0.97) and flow rate ($r=0.97$, $0.99$, $0.98$, and 0.99) was observed.

**Effect of Varying Pressure in the Receiving Chamber**

When flow rate and driving pressure across the orifice and volume of the receiving chamber were maintained constant and balloons of differing static compliances were studied, the spatial distribution of the jet decreased significantly as the pressure within the receiving balloon increased, although balloon volume was constant. The pressure inside the balloons was 57, 28, 18, and 8 mm Hg, respectively, for the compliances of 1, 2, 4.5, and 9 ml/mm Hg at this volume (150 ml). A similar pattern of variation was observed for flow rates varying from 100 to 270 ml/min (Figures 3 and 5, Table 1), but the amount of decrease in jet area with pressure was most striking at the higher flow rates. Therefore, the jet spatial distribution as assessed by color Doppler imaging tended to be progressively smaller as the pressure of the receiving chamber increased.

**Effect of Varying Both Volume and Pressure Together in One Balloon**

To assess the dependence of jet area on varying pressure and volume of the receiving chamber, we maintained constant flow rate and varied the volume of a different chamber: the receiving chamber volume was increased stepwise from 110 to 130 and 150 ml in a receiving chamber with static compliance of 2 ml/mm Hg. Receiving-chamber internal pressures of 5, 15, and 24 mm Hg were documented for the three balloon volumes, respectively. We evaluated flow rates of 160, 180, 200, and 225 ml/min. For each flow rate, the absolute jet area decreased progressively as the volume and pressure in the receiving chamber increased together (Figures 6 and 7).

In our model, as expected, higher flow rates still consistently produced larger jets except at the highest
chamber pressures and volumes, where the differences in jet sizes between the flow rates were smallest, but still significantly different (Figures 5 and 6, Table 1).

Last, we examined a final set of experiments in one of the balloons over the flat horizontal portion of its pressure–volume relation. In this experiment, major increases in volume could be induced without pressure change (constant pressure = 30 mm Hg); results showed a 50% increase in chamber volume, from 150 to 240 ml, with an insignificant (p = NS) change in jet area at four different flow rates, 160, 180, 200, and 225 ml/min.

Discussion

The limitations of color Doppler flow mapping to reliably quantitate the severity of valvular regurgitation based on the analysis of the spatial distribution of regurgitant jets are related not only to hemodynamic and instrument factors but also to the fact that the imaged jet actually depends on the regurgitant volume plus the entrainment of the surrounding fluid in the receiving chamber. In the light of these problems, initial applications of color flow mapping aimed toward quantitation seem naive. Despite these limitations, color Doppler jet area continues to be
extensively used in the clinical setting as a semiquantitative indicator of severity of valvular regurgitation. This semiquantitative approach will probably continue to be useful until recently proposed, more sophisticated quantitative methods can be proven to be clinically applicable. Recent preliminary clinical observations have suggested that the severity of acute valvular regurgitation is underestimated by color Doppler techniques when compared with angiography.

Because of some of these concerns about applicability of color flow mapping and differences between acute and chronic disease, we designed a simple constant flow model to study the influence of the pressure-volume relation inside the receiving chamber on the magnitude of spatial distribution of simulated regurgitant jets. Our results have shown that the pressure within the receiving chamber is an important determinant of the jet area visualized by color Doppler over a large range of constant flow rates. Additionally, we have documented that, for a balloon with a static compliance of 2 ml/mm Hg and a constant flow rate, the jet area decreased as the volume and ambient pressure of the receiving chamber increased. If jet size were normalized for receiving-chamber volume, as has been often suggested for clinical imaging, this underestimation would be significant. Thus, our data have shown that the pressure-volume relation in the receiving chamber is a major determinant of jet area as imaged by color Doppler flow mapping.

The intrinsic mechanisms for these changes are not clear. In the first experiment, differing compliance balloons were studied at constant volume (150 ml) so that the pressure inside these balloons varied from 57 to 8 mm Hg. In the second experiment, the compliance was constant, but both volume and pressure varied, respectively, from 110 to 150 ml and from 5 to 24 mm Hg. Thus, the pressure inside the receiving chamber seems to be the most important factor accounting for the observed changes in jet area. Most hydrodynamic investigations have dealt with behavior of free jets. To the best of our knowledge, there are no basic hydrodynamic studies or theoretical formulations evaluating the behavior of a "restrained" jet in a compliant chamber. We hypothesize that, as a consequence of higher levels of pressure inside the receiving chamber, the jet would have more rapid pressure recovery than at lower levels of pressure. Concordant with this, jet velocity would decrease faster to a level below the minimum detectable by color flow Doppler over a smaller distance than it would in a chamber with lower ambient pressure, resulting in a smaller jet area imaged by color Doppler flow mapping.
TABLE 1. Regurgitant Jet Areas at Different Flow Rates, Pressures, and Volumes Within the Receiving Chamber

<table>
<thead>
<tr>
<th>Flow rate</th>
<th>Regurgitant jet area (cm²)</th>
<th>ANOVA (constant flow rate)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Receiving-chamber pressure* (data from Figure 5)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>8 mm Hg</td>
<td>18 mm Hg</td>
</tr>
<tr>
<td>100 ml/min</td>
<td>2.70±0.2</td>
<td>2.20±0.13</td>
</tr>
<tr>
<td>150 ml/min</td>
<td>4.10±0.2</td>
<td>3.33±0.2</td>
</tr>
<tr>
<td>180 ml/min</td>
<td>5.30±0.2</td>
<td>5.23±0.22</td>
</tr>
<tr>
<td>225 ml/min</td>
<td>8.50±0.1</td>
<td>7.26±0.1</td>
</tr>
<tr>
<td>270 ml/min</td>
<td>10.2±0.2</td>
<td>8.68±0.1</td>
</tr>
<tr>
<td>ANOVA (constant pressure)</td>
<td>p&lt;0.0001</td>
<td>p&lt;0.0001</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Flow rate</th>
<th>Receiving-chamber volume† (data from Figure 6)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>110 ml</td>
<td>130 ml</td>
</tr>
<tr>
<td>160 ml/min</td>
<td>4.46±0.1</td>
<td>4.05±0.1</td>
</tr>
<tr>
<td>180 ml/min</td>
<td>5.97±0.2</td>
<td>5.20±0.2</td>
</tr>
<tr>
<td>200 ml/min</td>
<td>7.78±0.1</td>
<td>6.34±0.2</td>
</tr>
<tr>
<td>225 ml/min</td>
<td>9.10±0.3</td>
<td>7.97±0.1</td>
</tr>
<tr>
<td>ANOVA (constant volume)</td>
<td>p&lt;0.0001</td>
<td>p&lt;0.0001</td>
</tr>
</tbody>
</table>

Values are mean±SD. ANOVA, one-way analysis of variance.

*ANOVA reveals that regurgitant jet area significantly decreases for each increase in receiving-chamber pressure at all flow rates (all p<0.0001) but that regurgitant jet area is always higher at higher flow rates regardless of the receiving-chamber pressure (p<0.0001).

†In a single chamber of constant compliance (2 ml/mm Hg), as receiving-chamber volume (and pressure) increases, there is a significant (p<0.0001 by ANOVA) decrease in regurgitant jet area at all four flow rates, but regurgitant jet area is still higher at the higher flow rates at each volume and pressure combination.

Although our in vitro constant flow model is highly simplified compared with the much more complex pulsatile conditions and the dynamic compliance of chambers within the human heart, which also have concurrent inflow from other sources (such as pulmonary veins) into the receiving chamber and higher levels of flow and pressure gradients, it seems reasonable to expect that the observed effects of the pressure-volume relation on the color Doppler jet area should also occur under physiological conditions. On the other hand, our model has the advantage of permitting a rigid and individual control of all variables that potentially could affect the magnitude of regurgitation in the designed experiments.

The results from the present study may have important implications for the clinical evaluation of valvular regurgitation by color Doppler techniques, considering that the presence of regurgitation itself has significant consequences on the size and pressure in the receiving chamber and on the compliance characteristics of the receiving chamber. The nature of these changes depends on the rapidity and severity with which regurgitation develops. In acute and severe mitral regurgitation, for example, the atrial volume usually changes little, whereas the atrial pressure increases appreciably. On the other hand, in chronic severe regurgitation, the atrium is enlarged, but with greater compliance, and the atrial pressure increases only slightly or moderately. We would expect that, for the same regurgitant volume, maximum jet areas documented by color Doppler imaging would be smaller in patients with acute mitral regurgitation than in patients with chronic regurgitation.

The results of our study permit an explanation for the clinical observations recently reported by Harlament et al., who compared the severity of acute
Figure 7. Color Doppler flow images in the velocity-variance mode of simulated regurgitant jets at a flow rate of 200 ml/min in the receiving chambers with residual volume of 110 ml (upper panel), 130 ml (middle panel), and 150 ml (lower panel). Note that the magnitude of spatial distribution of the jet decreases as the residual volume increases.
and chronic mitral regurgitation by angiography and color Doppler flow mapping. These investigators have observed that comparable grades of acute and chronic mitral regurgitation by angiography were significantly different when analysis of the regurgitant jet area visualized by color Doppler was undertaken. The color Doppler jet areas were consistently smaller in patients with acute regurgitation compared with those with chronic valvular regurgitation of the same magnitude angiographically. Similar observations can be expected in patients who develop acute and severe aortic regurgitation with noncompliant left ventricles compared with patients who have the same magnitude of chronic aortic insufficiency but highly compliant ventricles.

In summary, the spatial distribution of regurgitant jets imaged by color Doppler flow mapping is highly dependent on the pressure–volume relation inside the receiving chamber. For the same regurgitant volume, jet area as assessed by color Doppler flow mapping decreases as the pressure of the receiving chamber increases. It would seem important, in light of the data of our study, to interpret the spatial distribution of regurgitant jets in individual patients with an awareness of whether they have acute or chronic disease. In a pulsatile system as in the clinical situation, with variations in driving pressure and jet flow rate during the cardiac cycle and with changes in receiving-chamber pressure, volume, and compliance during the period of regurgitation, these relations may be extremely complex. An improved understanding of hydrodynamics will be necessary to achieve true flow quantitation by color Doppler methods including considerations of the effects of receiving-chamber pressure and volume.

References
Color flow Doppler quantitation of regurgitant flow rate using the flow convergence region proximal to the orifice of a regurgitant jet (abstract). Circulation 1988;78(suppl II):II-609


KEY WORDS • color Doppler flow • pressure-volume relations • valvar disease • regurgitant jets
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