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Quantification of Mitral Regurgitation With MR Phase-Velocity Mapping Using a Control Volume Method

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Reliable diagnosis and quantification of mitral regurgitation are important for patient management and for optimizing the time for surgery. Previous methods have often provided suboptimal results. The aim of this in vitro study was to evaluate MR phase-velocity mapping in quantifying the mitral regurgitant volume (MRV) using a control volume (CV) method. A number of contiguous slices were acquired with all three velocity components measured. A CV was then selected, encompassing the regurgitant orifice. Mass conservation dictates that the net inflow into the CV should be equal to the regurgitant flow. Results showed that a CV, the boundary voxels of which excluded the region of flow acceleration and aliasing at the orifice, provided accurate measurements of the regurgitant flow. A large CV generally provided inaccurate results because of reduced velocity sensitivity far from the orifice. Aortic outflow, orifice shape, and valve geometry did not affect the accuracy of the CV measurements. The CV method is a promising approach to the problem of quantification of the MRV.

Index terms: Mitral regurgitation • Control volume • Regurgitant volume • Aortic outflow

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Abbreviations: CV = control volume. MRV = mitral regurgitant volume. PISA = proximal isovelocity surface area. PVM = phase-velocity mapping. VENC = velocity-encoding value.
been used to measure the mitral regurgitant volume in an indirect way, by subtracting the aortic outflow measured in systole from the mitral inflow measured in diastole (19). One of the disadvantages of this indirect method is that it is not valid in the simultaneous presence of mitral and aortic regurgitation.

In aortic regurgitation, the regurgitant flow rate can be measured with PVM by positioning an imaging slice perpendicular in the aorta close to the aortic valve (18). Integration of the aortic flow curve over diastole provides the regurgitant volume per cardiac cycle. Under the current imaging technology, this single slice technique is inaccurate in mitral regurgitation, because of the strong interaction between the aortic outflow and the regurgitant flow in the vicinity of the mitral valve (Fig. 1).

In a recent study, Walker et al (20) showed that flow through an orifice can be measured with a control volume (CV) method using PVM. Therefore, the idea in this study is to take a number of contiguous imaging slices in the vicinity of the mitral valve model and measure all three velocity components. Then, an imaginary CV is constructed to encompass the orifice. Because three-dimensional velocity data are available in all slices, it is easy to select a rectangular box (CV) in which the faces consist of voxels from these slices. One of the six faces of this box will cut the regurgitant orifice parallel to the orifice plane. Because of the principle of mass conservation, the net inflow into this box or CV (excluding the voxels inside the orifice) is equal to the regurgitant flow through the orifice.

Therefore, the hypothesis in this study was that this CV method has the potential to measure the mitral regurgitant volume. However, there is a need to determine the effect of a variety of factors on the reliability of the method to quantify the regurgitant volume. The aim of this study was to conduct an in vitro investigation for the potential of the CV method to accurately quantify the mitral regurgitant volume. Specifically, we investigated the effects of the size of the CV, the presence of aortic outflow, and the geometrical characteristics of the regurgitant orifice on the reliability and accuracy of the CV measurements.

**METHODS**

**Models**

A plexiglas left ventricular model (Fig. 2) with the aortic outflow tract was used for the experiments. The “base-apex” size was 7.6 cm, and the “anterior-posterior” size was 7.0 cm. The model was designed to allow cone-shaped plexiglas regurgitant mitral valve models to be inserted easily. Seven of these models were made to study different magnitudes of regurgitant flow rates and different geometries. Four of the models had a circular regurgitant orifice. Two of these circular orifice models had a cone-apex angle of 60° and the other two had an angle of 90°. For each angle, the orifice diameters used were 3 mm and 5 mm. The other three models had slit-like orifices with length to width ratios of 2.5:1, 5:1, and 10:1. The model was placed in a plexiglas vessel filled with stationary water to ensure an adequate MR signal.

**Measurements**

Steady and pulsatile flow experiments were performed in a 1.5-T scanner (Gyroscan ACS II, Philips Medical Systems, Shelton, CT). Water was used as the working fluid, because the flow in the model was inertially driven. Use of steady flow allowed the factors of interest to be investi-
Table 1: Experimental Conditions for the Steady Flow Experiments

<table>
<thead>
<tr>
<th>Orifice Type</th>
<th>Circular</th>
<th>Circular</th>
<th>Circular</th>
<th>Slit</th>
<th>Slit</th>
<th>Slit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (mm)</td>
<td>3</td>
<td>3</td>
<td>5</td>
<td>4 × 10</td>
<td>2 × 10</td>
<td>1 × 10</td>
</tr>
<tr>
<td>Cone-apex angle</td>
<td>60</td>
<td>90</td>
<td>60</td>
<td>90</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Regurgitant flow rate (l/min)</td>
<td>1.5</td>
<td>4.0</td>
<td>7.0</td>
<td>4.0</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Aortic outflow rate (l/min)</td>
<td>2.0</td>
<td>5.5</td>
<td>4.0</td>
<td>2.5</td>
<td>5.0</td>
<td></td>
</tr>
</tbody>
</table>

Table 2: Experimental Conditions for the Pulsatile Flow Experiments

<table>
<thead>
<tr>
<th>Orifice Type</th>
<th>Circular</th>
<th>Circular</th>
<th>Slit</th>
<th>Slit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size (mm)</td>
<td>3</td>
<td>5</td>
<td>4 × 10</td>
<td>2 × 10</td>
</tr>
<tr>
<td>Cone-apex angle</td>
<td>90</td>
<td>60</td>
<td>60</td>
<td></td>
</tr>
<tr>
<td>Regurgitant volume (ml/cycle)</td>
<td>10</td>
<td>40</td>
<td>35</td>
<td>55</td>
</tr>
<tr>
<td>Peak regurgitant orifice velocity (m/sec)</td>
<td>4.7</td>
<td>6.8</td>
<td>3.9</td>
<td>5.0</td>
</tr>
<tr>
<td>Rate (cycles/min)</td>
<td>60</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Net “cardiac” output (l/min)</td>
<td>4.2</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Imaging Procedure

Initially, a gradient-echo scout image was acquired, as shown in Figure 3 (slice thickness = 7 mm, field of view = 300 mm, TE = 8 msec, TR = 30 msec, flip angle = 35°, matrix size = 256 × 256). The mitral regurgitant orifice was detected on this scout image, and then five contiguous transverse velocity-encoded images, with all three velocity components measured, were acquired in the region of the regurgitant orifice (Figs. 1 and 3), perpendicular to the transvalvular axis (slice thickness = 5 mm; field of view = 300 mm; TE = 7.2, 5.4, and 6.9 msec for the through-plane, anterior-posterior, and left-right velocity components, respectively; TR = 30 msec; matrix size = 128 × 128; flip angle = 35°). The spatial resolution of the images (voxel size) was 5 × 2.34 × 2.34 mm. Although the in-plane resolution could be higher, increasing this resolution would cause an additional increase in the already long acquisition time. Because preliminary measurements with the 2.34 × 2.34 mm resolution provided accurate results, it was decided to perform the main measurements with this value. Based on preliminary measurements, the velocity-encoding value (VENC) used in the main experiments was 45 cm/sec. Use of this value prevented velocity aliasing in the region of interest in the vicinity of the regurgitant orifice. In pulsatile flow, each velocity acquisition was performed with retrospective ECG gating. Twenty phases were acquired during the cycle.

Image and Data Analysis

Based on the phase values of the pixels in the stationary water surrounding the model, a plane containing the phase offsets was created through two-dimensional regression analysis, as previously described in detail (18,21). Subtraction of this error plane from each initial phase image resulted in a series of new corrected phase images. Subsequently, the phase was converted to velocity based on the linearity between the phase of the received signal and the protons velocity. A computer program was used to select a series of rectangular CVs that encompassed the regurgitant orifice (Figs. 2 and 4). The range of rectangular CV sizes was from 7 × 7 × 7.5 mm to 40 × 40 × 22.5 mm (length × width × height). Integration of the velocity over the area of the faces of the CV (except for the pixels located on the mitral model wall and inside the regurgitant orifice) provided the net flow rate that entered the CV. Due to mass conservation, this flow rate should be equal to the regurgitant flow rate. In pulsatile flow, the regurgitant volume was determined by integrating the regurgitant flow curve over systole.

Statistical Analysis

The measured flow rates were compared to the actual flow rates with regression analysis. This analysis was
CV Height = 12.5 mm

Figure 4. Geometric characteristics of CV. Height corresponds to the base-apex direction (z or foot-head direction in the scanner); length corresponds to the anterior-posterior (or x in the scanner) direction; and width corresponds to the left-right (or y in the scanner) direction.

Figure 5. Relationship between the CV measured regurgitant flow rate and the actual regurgitant flow rate for small, medium, and large CV sizes.

Figure 6. Measured MRV with the CV method for an actual regurgitant volume of 55 ml/cycle.

Figure 7. Average percent error in the measured regurgitant volume for different CV length and width and for a CV height of three slices.

The same behavior was seen in the pulsatile flow measurements. A case of severe regurgitation is shown in Figure 6. Use of a small CV (7 x 7 x 7.5 mm) led to errors in the measurements. The accuracy was very good for a medium CV (21 x 21 x 12.5 mm). In Figure 7, the average percent error in the measured regurgitant volume is shown plotted against the CV length and width when the CV height is 12.5 mm (three slices). The variability in the measurements for each case can be seen from the error bars. In the case of small (<16 mm) or large (>26 mm) CV length and width, the variability is high and the reliability of the measurements is smaller compared to a medium CV size, in which both the mean errors and variability are small.

In Figure 5, the relation between the CV measured regurgitant flow rate and the actual regurgitant flow rate is shown. Results for three CV sizes are shown: small (7 x 7 x 7.5 mm), medium (26 x 26 x 17.5 mm), and very large (40 x 40 x 22.5 mm). For the small CV, the flow rate was measured satisfactorily only for very small flow rates. An underestimation in the measurements was seen as the regurgitant flow rate increased. Regression analysis confirmed the previous observations as seen from the regression equation. For the medium CV, the measured flow rates are in very good agreement with the true flow rates for the entire range of flow rates. This was confirmed by the regression equation. Use of a very large CV leads to underestimation of the flow rate and scattering in the data (reduced coefficient of determination).

• RESULTS

In Figure 5, no significant difference can be observed in the regurgitant volume results under different magnitudes of the aortic outflow (0-25 l/min). In all cases, even with no aortic outflow, best accuracy was observed for a medium CV (16-26 mm) length and width. The accuracy was reduced too close or too far from the orifice. Statistical analysis with a Mann-Whitney test confirmed the similarity of the results regardless of the aortic outflow rate (P values from .18 to .87).

No significant difference was observed in the results between the circular and the slit-like orifice shapes. This was also confirmed by statistical analysis with a Mann-Whitney test (P values from .37 to .96). Similarly, no significant difference was observed in the trends of the data for a 60° and a 90° cone-apex angle of the mitral valve models. Statistical analysis with a Mann-Whitney test confirmed the similarity in the measurements (P > .20).
**DISCUSSION**

The main current limitation of this approach is its long acquisition time. For instance, acquiring four slices, with factors, such as the ventricular wall motion and the aortic outflow interacts with the regurgitant flow. Other trival motion during systole, should be investigated next in the course of establishment of this method clinical deviations. For example, no wall motion was simulated because there were functional and geometrical physiological deviations. Of course, this model did not exactly represent the human left ventricle, showed that an interaction existed between the aortic outflow and the regurgitant flow (Fig. 9), similar to that observed from Doppler in vivo images. Of course, this model did not exactly represent the human left ventricle, because there were functional and geometrical physiological deviations. For example, no wall motion was simulated in the experiments. However, in this study, it was of interest to investigate whether the CV method is reliable in a flow environment similar to that observed clinically in patients with mitral regurgitation, in which aortic outflow interacts with the regurgitant flow. Other factors, such as the ventricular wall motion and the mitral valve motion during systole, should be investigated next in the course of establishment of this method clinically to measure the mitral regurgitant volume.

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**Figure 8.** Comparison between measurements of the regurgitant flow rate for different magnitudes of the aortic outflow.

**Figure 9.** Visualization of the flow field close to the mitral regurgitant orifice. LVOT = left ventricular outflow tract.

all three velocity components measured in each slice, required more than 1 hour of imaging. It should be pointed out that conventional pulse sequences were used in this study. Use of turbo gradient-echo, echo-planar flow imaging, and other ultrafast techniques (24,25) will provide short imaging times. These techniques are currently under investigation regarding their reliability and accuracy to measure blood velocity with promising results. The aim of this study was to show that the CV method is accurate using a well calibrated and extensively used pulse sequence.

Although the CV method is very promising in quantifying the regurgitant volume, mitral regurgitation is a complex disease. Several indices must be known before complete diagnosis is done. Knowledge of the regurgitant volume is important, because it provides an index of the severity of the disease. It can also be very useful in monitoring the effectiveness of drugs, such as vasodilators, used to treat patients with regurgitation and in following patients. This quantitative information combined with information regarding the condition and function of the heart that MRI provides can lead to a more complete cardiac evaluation.

In conclusion, in vitro measurements showed that the CV method is very promising for the quantification of the mitral regurgitant volume. The CV size must be selected...
carefully to be large enough for the boundary voxels to exclude the region of flow acceleration and velocity aliasing close to the regurgitant orifice. The presence of aortic outflow and the shape of the regurgitant orifice or the geometry of the valve do not affect the reliability and accuracy of the PVM measurements.

References