QUANTIFICATION OF THE MITRAL REGURGITANT FLOW USING A CONTROL VOLUME METHOD: IN VITRO EVALUATION USING ULTRA-FAST MAGNETIC RESONANCE VELOCIMETRY

Haosen Zhang (1, 2) Sandra S. Halliburton (1, 2, 3), Richard D. White (3), George P. Chatzimavroudis (1, 2, 3)

[1]Department of Chemical Engineering
Cleveland State University
Cleveland, OH

[2]Department of Biomedical Engineering
Cleveland Clinic Foundation
Cleveland, OH

[3]Section of Cardiovascular Imaging
Division of Radiology
Cleveland Clinic Foundation
Cleveland, OH

INTRODUCTION

Reliable diagnosis of the severity of mitral regurgitation is important for proper patient treatment and management. However, current clinical methods are either qualitative or limited by geometric assumptions. The only technique capable of bypassing these geometric limitations and quantitatively measure mitral regurgitation is velocity encoded magnetic resonance (MR) imaging, also known as phase-contrast MR velocimetry. This technique has been successfully used to quantify aortic regurgitation with a single image slice. However, due to the complex flow field proximal to the mitral regurgitant orifice in the left ventricle (LV) during systole, a single slice is not sufficient to measure the mitral regurgitant volume.

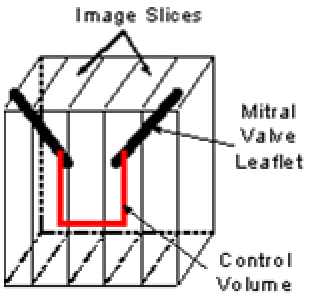

Figure 1. Control Volume Method

A multi-slice control volume (CV) method is thus necessary to provide accurate measurements of the mitral regurgitation volume (Fig.1). Phase-contrast MR is the only clinical technique to provide 3-directional (3-DIR) velocity data in an imaging slice. It has been shown *in vitro* that conventional non-segmented 3-DIR phase-contrast MR can accurately quantify the regurgitant flow using the CV method [1]. Despite this accuracy, the long duration of non-segmented phase-contrast MR prohibits a clinical multi-slice and 3-DIR velocity acquisitions within a routine cardiac MRI examination. Ultra-fast sequences are necessary to rapidly acquire the 3-DIR velocity data. Newly emerged segmented k-space phase-contrast MR could dramatically decrease the acquisition time from over one hour to less than 15 minutes. We recently showed *in vitro* [2] and *in vivo* [3] that ultra-fast segmented k-space phase-contrast MR can rapidly and accurately measure velocity and flow in straight tubes and in the human aorta. Therefore, the aim of this study was to evaluate the accuracy of this promising technique in quantifying the mitral regurgitant flow *in vitro*.

MATERIALS AND METHOD

Flow experiments were performed in a 1.5T Siemens Sonata clinical MR scanner using a Plexiglas LV model (Fig.2). The model included the aortic outflow tract and the mitral annulus that allowed insertion of the cone-shaped regurgitant mitral valve models. Four types of mitral regurgitant models were used (two with circular orifices, 3 and 5 mm inner diameter; two with slit-like orifices, 2.5:1 and 5:1 length-to-width ratio). Pulsatile flow studies, at a rate of 60 cycles/min, were performed using a Vivitro Systems piston pump, producing regurgitant volumes ranging from 10 to 60 ml/cycle under the presence of a physiological aortic outflow. The real flow volumes were known via a Transonic Systems transit-time ultrasonic flow probe.

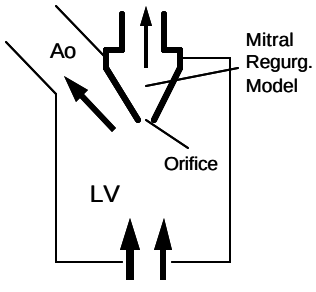

Figure 2. LV Model

Imaging Procedures

First, scout images were acquired to localize the mitral orifice. Then, five contiguous sagittal imaging slices (slice thickness 5 mm; field of view 250x250 mm^2) were positioned in the orifice region (Fig.1), and 3-DIR (one through-plane and two in-plane) velocity acquisitions were performed in each slice using: (a) a non-segmented gradient-echo sequence ("non-seg"); (b) a segmented turbo gradient-echo sequence with 7 k-space lines per segment ("seg-7"); and (c) a segmented turbo gradient-echo sequence with 9 k-space lines per segment ("seg-9"). The "non-seg" acquisition was performed to provide the reference data in addition to flow probe readings. The velocity aliasing limit (V_{ENC}) was varied between 150 and 250 cm/s. Each "non-seg" scan (one slice, one velocity component) required approximately 180 seconds, whereas each "seg-7" or "seg-9" scan required only 10-15 seconds.

Data Analysis

The image data were processed by selecting a range of CV sizes encompassing the orifice and integrating the velocity over the faces of the CV (excluding the pixels in the orifice) to find the flow rate. Then, additional integration over "systole" provided the regurgitant volume. Statistical analysis was performed to compare the "seg-7" and "seg-9" data with the real flow results and with the "non-seg" data. The three dimensions of the CV were defined as (refer to Fig.1): x (into the page), CV width; y (left to right), number of slices; z (top to bottom), CV height.

RESULTS AND DISCUSSION

Fig. 3 shows the measured regurgitant flow rate during "systole" for a circular orifice from the "seg-7" sequence for a *small* (defined to have a z-size of 3 mm) and a *larger* CV height (defined to have a z-size of 7 mm), under a real regurgitant flow volume of 30 ml/cycle. Three slices (y-size) and an x-size of 11 mm were considered in both cases, based on previous preliminary steady flow data. The mean difference between the measured "systolic" regurgitant flow volume and the real value was 21.8% and 1.5% for the *small* and *larger* CV height cases, respectively. Selection of a *larger* CV height also provided close agreement between the "seg-7" and the "non-seg" data (5% difference). The non-parametric Freidman's Rank Test showed a statistically significant difference ($p<0.05$) between the *small* CV height and the *larger* CV height results.

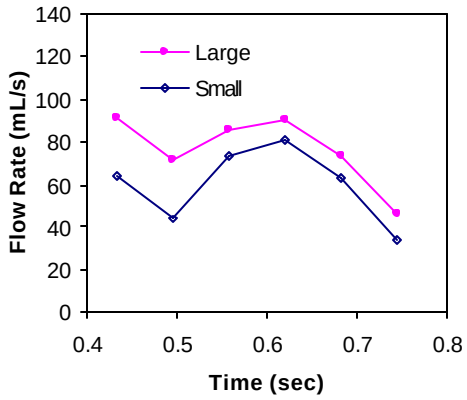

Figure 3. Pulsatile Flow During Systole

Fig. 4 shows the measured flow rates during the entire "cardiac cycle" for a slit-like orifice using the "non-seg", the "seg-7" and the "seg-9" sequences for the *larger* CV dimension (x size of 11mm, z size of 7 mm), under a real regurgitant flow volume of 40 ml/cycle. The calculated regurgitant volumes (determined by integrating the flow curves over "systole" only) were 40.8, 41.6 and 41.9 ml/cycle for the "non-seg", the "seg-7" and the "seg-9" separately. Freidman's Rank Test also showed no significant differences ($p>0.05$) among the "seg-7", the "seg-9", the "non-seg" and the real flow volume values during "systole". However, the use of a *small* CV height or width resulted in 30% underestimation of the real flow volume.

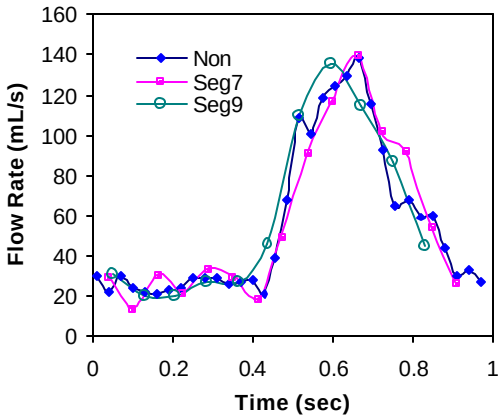

Figure 4. Pulsatile Flow Waveform with Different Sequences

In general, the measurements were inaccurate when the CV was so small (height<5 mm; width<7 mm) that its boundary faces were too close to the orifice. This was due to signal (and velocity information) loss and velocity errors caused by flow acceleration and velocity aliasing. When the CV was large enough for its boundaries to be outside this region of signal loss, the measurements were accurate.

CONCLUSIONS

Rapid segmented k-space phase-contrast MR can accurately quantify the flow through orifices simulating regurgitant mitral valves and, therefore, demonstrates great clinical potential. However, caution should be taken in order to exclude the CV boundaries outside the region of velocity aliasing and flow acceleration to minimize errors in the velocity acquisitions.

REFERENCES

1. Chatzimavroudis G. P., Oshinski J. N., Pettigrew R., I., Walker P. G., Franch R. H., Yoganathan A. P., 1998, "Quantification of Mitral Regurgitation with Magnetic Resonance Phase Velocity Mapping Using A Control Volume Method," JMRI. Vol. 8, pp. 577-582.
2. Zhang H., Halliburton S. S., Moore J. R., Simonetti O. P., Schvartzman P. R., White R. D., Chatzimavroudis G. P, 2002, "Ultrafast Flow Quantification with Segmented *k*-Space Magnetic Resonance Velocity Mapping," Annual of Biomedical Engineering, Vol. 30, pp. 120-128.
3. Chatzimavroudis G. P., Zhang H., Halliburton S. S., White R. D., "Clinical Blood Flow Quantification With Segmented k-Space Magnetic Resonance Phase Velocity Mapping," JMRI. (In press).