

# Vortex Ring Formation in Diastolic Dysfunction: Phase Contrast MRI of Left Ventricular Filling

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## Introduction

The formation of vortices during left ventricular (LV) filling (Fig. 1) has been noted in several investigations using phase contrast (PC) MRI [1,2], but the effect of diastolic dysfunction (DD) on vortex formation has not been investigated. We hypothesize that impaired relaxation (IR) and increased stiffness of the LV wall in DD, will substantially alter the kinetics of the vortices, which are highly sensitive to chamber properties. If true, quantitative measurements of vortex kinetics could fill the need for a continuous, non-invasive measure of diastolic function, which is currently lacking. In this pilot investigation a standardized method for visualizing and quantifying the LV vortex ring was developed and used to compare measures of LV diastolic vorticity in both normal and IR subjects.

## Theory and Methods

The two primary vortices visible in Fig. 1A represent two halves of a single vortex ring that is bisected by the long axis image plane. From a PC-MRI series encoded for the two in-plane components of velocity, the vorticity,  $\partial v_x/\partial y - \partial v_y/\partial x$ , can be computed. Fig. 1B shows the corresponding vorticities with positive values encoded in red and negative values encoded in blue. To sample the entire vortex ring, we developed a PC-MRI protocol in which 6-9 image planes are placed at equal angular spacing around an axis that extends from the center of the inflow jet to the LV apex. The circumferential component of vorticity is computed for each pixel and the set of images is reformatted into a short axis slab extending from the tips of the mitral leaflets at end-diastole to a location 3 cm toward the apex (a zone found to consistently contain the entire vortex ring). The vorticity values within the slab are then projected to a single short axis image plane. The integrated vorticity values are displayed with a color-coded map ranging from 0 (blue) to 500 cm/s (red). This protocol was used to image 5 normal subjects and 5 subjects with IR by echocardiographic standards [3] on a 3T Philips Achieva scanner. To facilitate comparison of the timing of diastolic vortex rings, time frames were indexed to the diastolic interval bounded by end-systole (defined as the end of mechanical contraction on CINE imaging) and end-diastole. For all diastolic time frames, the total circulation was computed as the integral of vorticity within the LV chamber.

## Results

Fig. 2A shows the approximate viewing geometry and circular region within which vorticities are depicted. Fig. 2B shows corresponding time frames in a normal subject (left column) and one with IR (right column). The formation of a complete vortex ring is observed, that is slightly elongated in the direction along the mitral leaflets. In the IR subject, a slight delay and weakening is observed for the ring associated with early filling (E), which is compensated by an increase in the magnitude of the ring associated with atrial contraction (A). Quantitative comparisons (Fig. 3; normal subjects solid blue, IR dashed red) showed that the E-ring peak circulation was significantly weaker in IR (1888 cm<sup>3</sup>/s vs. 3022 cm<sup>3</sup>/s; p=0.03) and was nearly significantly delayed relative to normal subjects (diastolic time index of 0.334 vs. 0.242; p=0.10). In addition, trends were observed in IR for higher A-ring peak circulation (1702 cm<sup>3</sup>/s vs. 1311 cm<sup>3</sup>/s; p=0.11) and higher minimum circulation values in the trough between peaks (417 cm<sup>3</sup>/s vs. 91 cm<sup>3</sup>/s; p=0.14). Finally, the E/A vorticity ratio was significantly higher for normal vs IR subjects (2.4 vs. 1.1; p=0.003). General metrics of heart function including heart rate were not significantly different between groups.

## Conclusions

In this study, we have shown that visualization and quantification of the LV diastolic vortex rings are feasible in both normal and IR subjects using a standardized method. Moreover, despite the small size of this pilot study, several significant and nearly significant between-group differences were detected. Specifically, in IR subjects, the E-ring is delayed and reduced in magnitude, the A-ring is increased, and there appears to be greater persistence of between-peak vorticity. Thus the methodology used to quantify diastolic vorticity is able to detect differences between normal and IR subjects. The current echocardiographic measures of diastolic function, on the other hand, are load-dependent, do not provide a continuous quantitative indication of severity, and exhibit a high error rate for staging DD compared with invasive measures [4]. Thus, diastolic vorticity quantification with PC-MRI holds promise as an improved non-invasive means of detecting and staging DD severity. To verify this potential, further investigations are warranted, including validation using invasive, high-fidelity catheterization techniques to measure Tau, the time constant of relaxation.

## References

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- [3] Zile, Brutsaert. Circulation 105:1387-93, 2002.
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Fig. 1

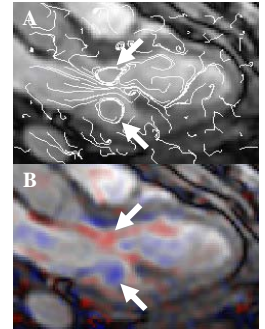


Fig. 2

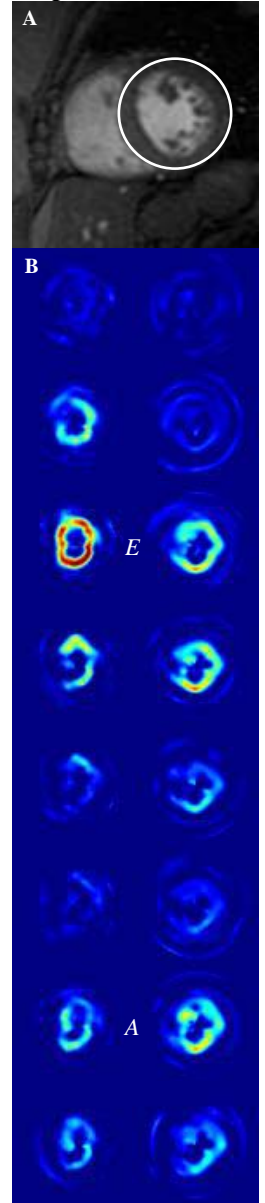


Fig. 3

