CONTRIBUTION OF EARLY AND LATE FILLING VORTEX RINGS TO NORMAL LEFT VENTRICULAR FLOW: QUANTITATIVE 4D FLOW MRI ANALYSIS USING 3D VORTEX CORES COMBINED WITH PARTICLE TRACING

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Purpose: Vortex formation in the left ventricle (LV) during diastolic filling has been confirmed by many *in vivo* and *in vitro* studies. Although many studies have postulated a potentially important role of vortex formation on the efficiency of cardiac pumping function, only limited knowledge is currently available on the actual contribution of the intrinsically three-dimensional (3D) vortex formation during diastole to the normal intra-cardiac blood flow *in vivo*. In this work, using 4D Flow MRI from ten healthy volunteers, we applied 3D vortex core analysis in combination with particle tracing to quantify the contribution of early and late filling 3D vortex rings to the normal LV flow over the cardiac cycle.

Methods: The study included ten healthy volunteers (age: 25±15, 5 male). All subjects underwent whole-heart 4D Flow MRI performed on 3 Tesla MRI (Philips, Netherlands) with free breathing, echo-planar-imaging to factor of 5, three-directional velocity encoding of 150 cm/s in all directions, spatial resolution 2.3×2.3×3.0 mm^3 and 30 phases reconstructed over one cardiac cycle. We used a previously validated method to detect vortex cores within the LV cavity[1]. In short, the 3D LV endocardial boundaries were manually segmented from 4D flow MRI over the cardiac cycle. Then, the Lambda2 -method was applied to the segmented LV cavity to detect 3D vortex ring cores at the phases of peak early filling (E-vortex) and peak late filling (A-vortex). The detected vortex ring cores were represented as isosurfaces of a manually adjusted isovalue of the Lambda2–volume that provided the most compact (least trailing structures) and circular vortex ring core. To determine the contribution of blood contained in the vortex ring core as part of the global intra-cardiac flow organization, two steps were performed: 1) Using the method of Eriksson et al. [2], particles were emitted from the complete LV cavity at the time of end-diastole (ED) and traced backward (for diastole) and forward (for systole) in time. Based on the location of the traced particles at the start and the end of the cycle, the LV flow was then separated into the four different flow components: Direct Flow (blood that enters and leaves the LV in one cardiac cycle), Retained Inflow (blood that enters LV but does not leave during systole of a single cardiac cycle), Delayed Ejection Flow (blood initially residing in LV during diastole and leaving during systole) and Residual Flow (Blood that remains inside the LV for at least two cardiac cycles). 2) The same procedure was repeated but instead of seeding from the LV cavity at ED, the particles were seeded from the voxels within the detected early and late vortex ring cores. The four components of the vortex flow were subsequently determined and the proportions of the four vortex flow components computed. The contribution of vortex ring flow to the total LV flow components was computed as fraction of vortex ring flow components to the total LV flow components. Peak early and peak late filling vortex rings were seeded independently to define the contribution of each vortex ring to the total LV flow components.

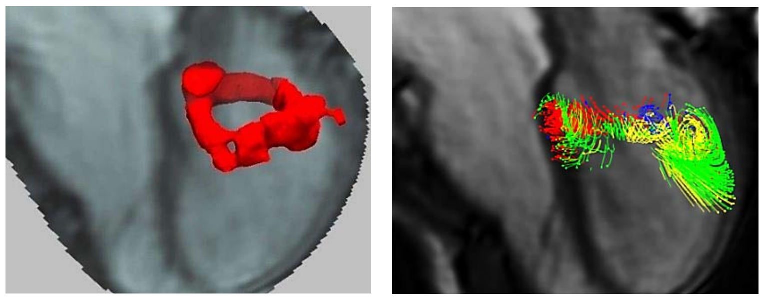

Figure 1: (left) LV peak E- filling vortex ring core isosurface (in red) identified using lambda2 method. (right) particles seeded form within the vortex ring core isosurface of peak early filling and traced for 120 ms (RR=1051 ms , peak early filling at 490 ms).

Results: In all subjects vortex ring cores were detected at both peak early and peak late filling (Figure 1). Most of the blood in vortex ring core during both early and late filling was ejected during one cardiac cycle (direct flow: E-vortex= 57 ± 12% and A-vortex= 70±13%, respectively), while almost all blood from the vortex ring core flow was ejected within two cardiac cycles with only small amount of residual flow (Residual Flow: E–vortex=2±4% and A-vortex 0.8±2% , respectively) (Figure 2). The total LV flow components were separated into Direct flow (43 ± 9%), Retained Inflow (21± 7%), Delayed Ejection (19± 5%) and Residual Flow (16± 4%) of the total ED volume (EDV). Detailed results are provided in Table 1and Figure 2. The peak early filling vortex ring core contributed to 11±7% of the total LV direct flow, while peak late filling vortex ring core contributed to 11± 0.05% of the total transported direct flow. The fraction (relative to EDV) of vortex ring core volume was (8±3%) for peak early filling vortex ring core and (6±2%) for peak late filling vortex ring core.

Discussion and conclusion: The findings quantitatively demonstrate the significant contribution of vortex ring formation, by means of vortex cores, during both early and late filling to the efficient transportation of the diastolic blood inflow towards its systolic ejection. With most vortex flow fraction being ejected during one cardiac cycle (i.e. direct flow) and only small fraction of vortex flow being residual flow, this suggests a role of vortex ring formation in efficient coupling of the diastolic inflow with systolic outflow in normal hearts. This work might provide more insights on the blood transportation mechanism of the normal heart therefore allow more understanding of potential associated pathologies.

Table 1: Proportion of the four vortex ring flow components

	Direct Flow %	Retained Inflow %	Delayed Ejection %	Residual Flow %
Peak early filling vortex ring core flow components	58 ± 12	22 ± 9	18 ± 9	2 ± 4
Peak late filling vortex ring core flow components	70 ± 13	11 ± 10	18 ± 10	0.8 ± 2
Fraction of Peak early filling vortex ring core flow to the total LV Flow components	11 ± 7	8 ± 3	7 ± 5	0.8 ± 1
Fraction of Peak late filling vortex ring core flow to the total LV Flow components	11 ± 0.05	3 ± 0.02	6 ± 0.03	0.2 ± 0.00

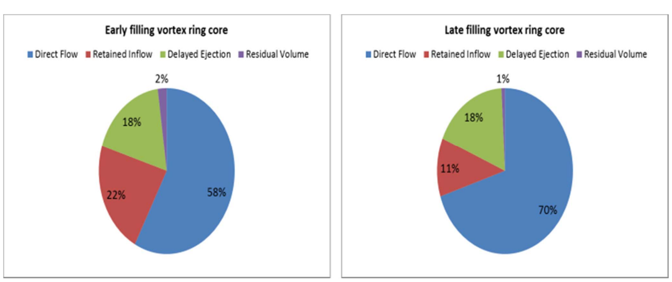

Figure 2: Flow components of peak early filling vortex ring core (left) peak late filling vortex ring core (right). Most vortex flow is direct flow (i.e. ejected during one cardiac cycle**).**

References:

[1] Elbaz et al. JCMR (2014) 16:78 [2] Eriksson et al.: JCMR (2010) 12:9.