

Blood Flow Patterns in the Left Ventricle of the Healthy Human Heart Described by Lagrangian Coherent Structures Computed from 4D Phase Contrast MRI

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Background: The flow patterns in the human left ventricle are not yet completely understood. Three-dimensional, time-resolved Phase Contrast Magnetic Resonance Imaging (4D PC-MRI) may provide new insights. However, blood flow in the human heart is complex and cannot be displayed directly in its entirety. Therefore, a simplified view is desired. Flow visualization using Lagrangian Coherent Structures (LCS) [1] offers one such simplification by dividing the flow into regions with dynamically distinct behavior. One example of an LCS is the boundary between blood that flows into the left ventricle during diastole, and the blood that was already in the left ventricle from the previous heartbeat. Since the shape and position of this boundary is a basic aspect of the blood flow, it may be connected to the heart's pumping function and studying it may lead to new insights into cardiac function. The existence of the LCS described here has previously been shown in a small number of healthy volunteers by studying two-dimensional slices through the structures. However, the three-dimensional shape and position of LCS in 4D PC-MRI data from the human heart have not been described before.

Purpose: The purpose of this study was to investigate the three-dimensional shape and position of the LCS in the left ventricle marking the boundary between inflow blood and blood that was already in the ventricle from the previous heartbeat in healthy volunteers. Additionally, we aimed to describe similarities and differences between the volunteers.

Methods: Three-dimensional, time-resolved, three-component Phase Contrast MRI (4D PC-MRI) was used to measure velocity fields over the whole heart and ascending aorta in four healthy volunteers (one female, subject 1, and three male, subjects 2-4). The spatial resolution was 3 mm isotropic, temporal resolution 50 ms, and VENC 100 cm/s. Using advanced numerical methods, the destination of every fluid particle in the heart was computed, producing a *flow map* from the beginning of diastole to the end of diastole. Since the studied LCS separates blood with different origins, the computed flow map will have a large spatial variation near the LCS. An algorithm developed in-house was used to find surfaces in three dimensions with locally high variation of the flow map, corresponding to LCS. LCS inside the left ventricle were then visualized in each subject using a commercially available software package (Ensign, CEI, USA) along with CINE images of the heart and the 4D PC-MRI velocity fields.

Results and Discussion: The LCS separating inflow blood from the blood already in the left ventricle from the previous heartbeat was computed successfully in all four subjects. In the Figure, the results of the computation and visualization are shown for subject 2. Note how the inflow curves along the lateral wall of the left ventricle towards the apex. This suggests a swirling motion of the blood flowing into the left ventricle. In subjects 1 and 3 the inflow blood LCS formed a direct path towards the apex. In subject 4 there was also a straight path towards the apex, but the surface was less regular. This suggests a more irregular inflow into the left ventricle.

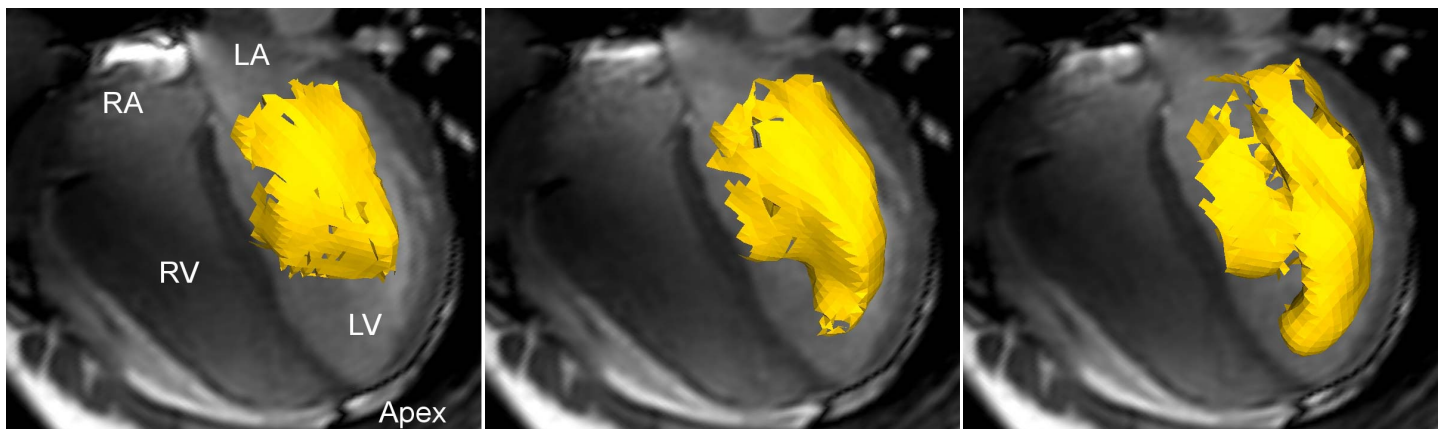


Figure: LCS visualization of the filling of the left ventricle (LV) in subject 2. A CINE image of the heart in the four-chamber view is displayed in the background for orientation. Left: Mid-diastole. Note the left ventricle (LV), the right ventricle (RV), the right atrium (RA), the left atrium (LA) and the tip of the left ventricle, the Apex. The yellow surface is the LCS marking the boundary between inflow blood (inside the surface relative to the viewer) and blood that was already in the ventricle since the previous heartbeat (outside the surface). Middle: Mid-late diastole. The boundary LCS has moved towards the apex and curved slightly clockwise. Right: End diastole. The boundary LCS has moved further towards the apex and has been additionally deformed.

Conclusions: The three-dimensional shape and location of the LCS marking the boundary between inflow blood and blood that was already in the ventricle from the previous heartbeat varied between the subjects. The reasons for the differences are not clear, and the significance for cardiac function remains to be studied.

References: 1. Shadden, Lekien, Marsden: *Definition and properties of Lagrangian coherent structures from finite-time Lyapunov exponents in two-dimensional aperiodic flows*, Physica D 212, 271 (2005).