Automatic Detection of Vortical Flow Patterns from Three-dimensional Phase Contrast MRI

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Introduction

Interaction between vortical flow and cardiovascular structure has a potential of bringing new insights to understanding the blood flow in the human heart. Vortices in the human heart have previously been reported by use of phase contrast MRI by [1]. The importance of vortices is still unknown. Suggestions have been made that left ventrical vorticies may have benificial effects in avoiding left atrial stasis [2], and facilitating mitral valve closure [3]. Manual vortex identification is time-consuming and operator dependent.

Even though vortices are of fundamental importance in fluid dynamics a unique definition does not exist. Automatic tracking methods have been proposed, but are limited to two-dimensions [1], or not applicable to phase-contrast data. As vortices are never limited to a plane, a three-dimensional (3D) method is necessary. Most of vortex detection algorithms in the literature are based on the theory of critical points. One disadvantage with these methods is that the may produce spurious results in the case of spiraling flows or skewed vortical flow [5], and, as they are developed for simulation data, need a high resolution and high signal-to-noise ratio. We propose a novel similarity measure between an idealized vortex pattern and a vector field. With this approach we gain insensitivity to noise since we are looking for a similarity in a region instead of looking locally in one point.

Methods

A 3D cine phase contrast pulse sequence [4] was used on a 1.5 Tesla Signa Horizon EchoSpeed scanner (GE Medical Systems, Milwaukee, WI, USA). Velocity vector information was obtained in a 3D grid encompassing the heart, and 16 time frames during the cardiac cycle were acquired in a healthy volunteer. Acquisition parameters included: TR=18 ms, TE=6 ms, VENC=60 cm/s, FOV=30x30x12.8 cm. A 256x74x28 k-space matrix was used, covering only a cylindrical part of k-space in order to minimize the scan time. 2D cine images were also obtained for a better anatomical definition. The phase contribution from concomitant gradient (Maxwell) terms to each of the four velocity encoding echoes was calculated and subtracted.

Similarity measures for vortex core identification have to our knowledge only been used in two-dimensional vector spaces. The situation is more complicated for 3D since a vortex can be rotated arbitrary, and thus no standard correlation techniques can be used. A possible method would be to use many rotated patterns and standard correlation or filtering techniques. There are however more efficient ways to do this by using image processing techniques originally developed for estimation of local orientation in image volumes. The tensor approach presented by H. Knutson [6] can be extended to detect similarity to a vortex-core pattern and orientation of the vortex core. In order to detect weak vortices, the velocity field is normalized prior to the application of the algorithm. The similarity tensor, $\mathbf{T}$, can be constructed as a direct summation of the squared convolution result between the normalized input velocity field $\mathbf{v}$ and the six vortex core patterns $\mathbf{f}_k$ as:

$$\mathbf{T} = \sum_{k=1}^{6} \left\langle \mathbf{f}_k * \frac{\mathbf{v}}{\|\mathbf{v}\|} \right\rangle^2 \left(\frac{5}{4} \hat{\mathbf{n}}_k \hat{\mathbf{n}}_k^{\mathbf{T}} - \frac{1}{4} \mathbf{I} \right)$$

This assumes that the symmetry axes of the six patterns $\mathbf{n}_k$ are oriented towards the vertices of an hemi icosahedron [6]. The similarity tensor is interpreted in terms of its eigenvalues and eigenvectors. The largest eigenvalue of the tensor gives the similarity or 'likelihood' of being a vortex core and its corresponding eigenvector the symmetry axis of the vortex core. Two of six vortex filters, $\mathbf{f}_k$ are illustrated in Figure 1.

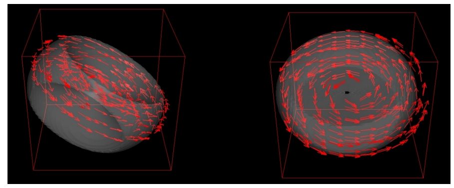

Figure 1. Illustration of two of the six vortex core filters.

Results

From the resulting similarity measure an isosurface can be calculated to visualize regions with vortical flow (Figure 2). In the figure a pair of vortices can be seen behind the mitral leaflets, and one vortex in the left atrium. To verify that vortices were found streamlines showing the instantaneous flow pattern were emitted from the isosurfaces.

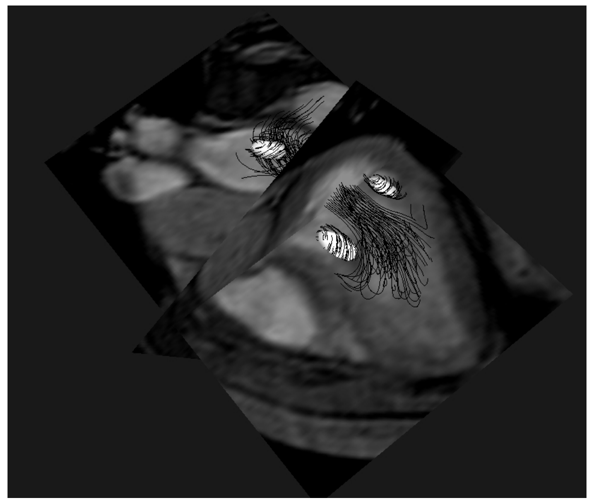

Figure 2. Vortices in a healthy volunteer, visualized as white isosurfaces. A pair of vortices can be seen behind the mitral leaflets and one vortex in the left atrium.

Conclusions

Using time-resolved three-dimensional phase contrast data and the proposed method it is possible to fully automatically identify and track vortices in the human heart. This method assures that all cardiac vortices are identfied and facilitates studying their behavior over time.

References

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