Vortical Flow Feature Characterisation using MR Velocity Mapping

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Introduction

Patterns of blood flow in space and time vary with cardiovascular shape and dynamics. Understanding interactions between vortical fluid movement and cardiovascular structure has a potential role in studies of cardiovascular function [1]. The purpose of this work is to derive a systematic way of studying vortical flow features using multi-directional MR phase velocity mapping. The technique relies on the phase portrait method to identify and analyse the dynamics of vortical flow patterns which are characterised by their circular or swirling motion. The method is concentrated on the topological aspect of in vivo flow structures and is suited to the study of complex flow patterns depicted by MR velocity mapping techniques.

Method

The theory used for automatic flow feature recognition is the phase-portrait method used in exploring the properties of solutions of ordinary differential equations [2-3]. This method does not yield a complete solution, but by locating certain critical points and linearizing about them, the topological features of the solution trajectories can be explored. Any set of ordinary differential equations which are autonomous may be written without loss of generality as a set of coupled first-order equations. For example, consider the cases where the solution is sought in a single plane we have

\[
\begin{align*}
\dot{x} &= P(x, y) \\
\dot{y} &= Q(x, y)
\end{align*}
\]

where \( P(x, y) \) and \( Q(x, y) \) are continuously differentiable functions. The solution to the system described above equations may be plotted in the \((x, y)\) plane known as the phase plane or phase space and it represents the trajectories of particles in a dynamic system. When \( P \) and \( Q \) represent the \( x \) and \( y \) components of a velocity vector \( \mathbf{v} = (v_x, v_y) \), the vectors depicted are tangential to the streamlines of the flow field. Critical points of the system are defined as points where \( \dot{x} = \dot{y} = 0 \). These may be equilibrium positions where in-plane motion terminates.

In general, \( P(x, y) \) and \( Q(x, y) \) are nonlinear functions. However, in the vicinity of a critical point, the equations are linearizable and may be expressed in a matrix form as

\[
\begin{bmatrix}
\dot{x} \\
\dot{y}
\end{bmatrix} =
\begin{bmatrix}
a_{11} & a_{12} \\
a_{21} & a_{22}
\end{bmatrix}
\begin{bmatrix}
x-x_0 \\
y-y_0
\end{bmatrix} = A(x-x_0, y-y_0)
\]

The two eigenvalues \( \lambda_1 \) and \( \lambda_2 \) of matrix \( A \), which in general may be real or complex, govern the qualitative behaviour of the system.

To identify all critical points located within the flow field, we used the concept of index or winding number commonly used in qualitative analysis of dynamical systems. This is then followed by a structure filtering process which incorporates the eigenvalues of matrix \( A \) so that only those points associated with vortices are highlighted. To analyse the temporal behaviour of detected vortices, a dynamic tracking algorithm was developed to follow automatically the motion of salient vortex structures.

The effectiveness of this technique for studying blood flow features was validated using a numerical phantom and data acquired from normal subjects with aortic aneurysm and left ventricular dilatation. The difference in vortex flow dynamics has been compared. All images in this study were acquired using a Picker International Vista MR machine operating at 0.5T with modified gradient coils and a surface receiver coil. Cine phase shift velocity mapping was performed using a FEER sequence with an echo time of 14 milliseconds. The slice thickness used was 10mm and the field of view was 30 cm or 40 cm. The images were reconstructed on a 256x256 matrix using 128 phase-encoding steps with two averages. For in vivo studies, sixteen cine frames were acquired for each directional velocity map and were gated from the onset of the ECG (electrocardiogram) R wave.

Results

The figure below shows the result for one of the patients with ascending aortic aneurysm due to Marfan’s syndrome. The associated flow pattern within the ascending aorta showed a central forward stream, slightly skewed to the right in relation to the patient, with vortices developing on either side of the main flow stream. The vortices lasted through systole and most of diastole. The trajectories of these two vortices characterised by the described technique demonstrate the amount of movement is not seen in the normal subject, where vortices remain within the sinuses above the aortic valve. The associated vorticity and the area covered by each vortex is delineated in the following graph. In the early part of the cardiac cycle, the left lateral vortex (B) is more significant, both in terms of size and vorticity. With a slower decay in vorticity, the right lateral vortex (A) gradually takes over dominance.

Conclusions

In this study, we proposed the approach of detecting salient topological features prior to analytical analysis of dynamical indices of the fluid. Critical points are the salient features of a flow pattern; given a distribution of such points and their type, much of the remaining flow field and its geometry and topology can be deduced. This method of using qualitative topological descriptors gives an insight into the structure of flow fields and provides a reference for interpreting the numerical results.

References