Vortex core detection and visualization using 4D flow-sensitive MRI

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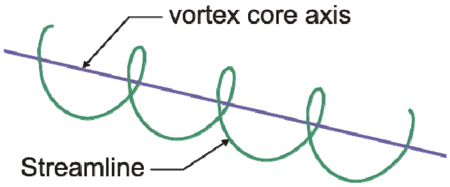
Introduction: A number of studies have shown that flow patterns such as vortex or helix flow may play an important role in the development of vascular disease by altering shear forces at the vessel wall thereby promoting atherosclerosis formation (1-3). With the progress of flow-sensitive MRI acquisition and visualization techniques, there is a growing interest for the detection and identification of swirling and vortical blood flow (4-7). The present methods often consist in visualizing flow fields, streamlines or particle traces whose analysis can be tedious and subjective. Vortex analysis is important as well for the aerospace industry where vortex core detection techniques are already used (8,9). Some of these techniques were already applied to flow-sensitive MRI datasets for the detection of blood vortex within the heart and arteries (6,10,11). In this work, a vortex core detection technique (9) was used in combination with a 4D flow visualization approach for the detection and visualization of vortex cores within 4D flow-sensitive datasets.

Fig.1: Schematic representation of one streamline and of the corresponding axis of vorticity.



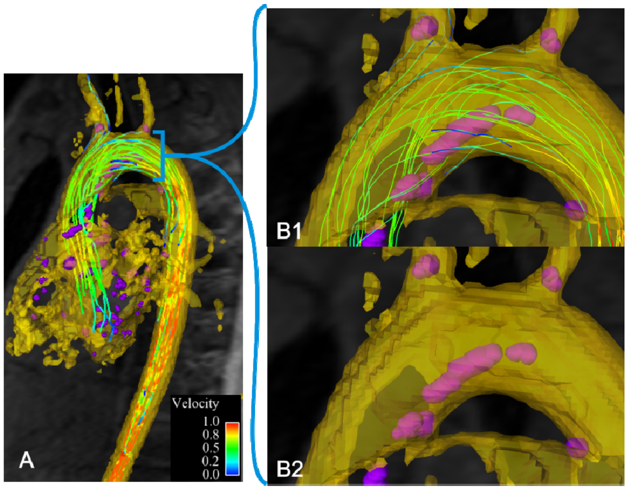


Fig.2: Streamline visualization and vortex core detection (purple spheres) in the healthy aorta at end-systole.

Methods: Data was acquired using 3T MR systems (Magnetom Tim TRIO, Siemens, Germany) with a 4D flow-sensitive MRI sequence (12) in the aorta (3 volunteers and 1 patient with aortic aneurysm (4)), the carotid arteries (2 volunteers) and intracranial arteries (3 patients (6)). All data were subsequently corrected for eddy currents and phase-contrast angiographies (PCMRA) were calculated (13). 3D blood flow was visualized using 3D visualization techniques such as vector plots, streamlines or particle traces (EnSight, CEI, Apex, NC). The vortex detection (Fig.1) was based on an eigenvector analysis of the rate-of-deformation tensor at every point. The centers of local swirling flow (or vortex cores) were identified at points where the rate-of-deformation tensor had one real and a pair of complex-conjugates eigenvalues as well as null reduced velocities (9). The vortex cores were visualized using spheres with a diameter depending on the root-mean-square of the local vorticity.

Results: No major swirling flow patterns were observed in the aorta of the healthy volunteer (Fig.2A) but vortex cores of limited amplitude were detected at end-systole in the aortic arch (Fig.2B). These findings correspond well to the typical outflow helix in the ascending aorta and arch of normal subjects. In the patient with aortic aneurysm, streamline analysis revealed swirling flow patterns inside the aneurysm and the distally attached descending aorta during early-diastole (Fig.3A-B). The vortex core detection algorithm identified vortex cores at the center of these swirling flow patterns (Fig.3B-C). Interestingly, the major vortex orientation changed rapidly from horizontal within the aneurysm to longitudinal distal to the aneurysm which was clearly depicted by the 'T' shaped vortex cores (Fig.3C). Vortex cores were identified as well in the internal carotid artery (ICA) but not in the external carotid artery (Fig.4). Interestingly, the ICA bulb presented two helical flow channels.

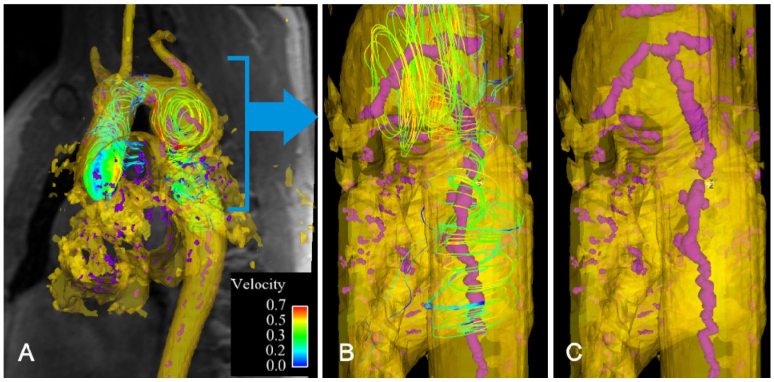


Fig.3: Aortic aneurysm patient: streamline visualization (A-B) and vortex core detection (purple spheres, B-C) in the thoracic aorta at early-diastole.

Discussion: 3D swirling flow analysis based on velocity vector fields, streamlines or particles traces, can be tedious because of the 4D nature of the data (observer-dependence of the location of analysis planes, swirling flow patterns possibly hidden by other streamlines). The vortex core detection provided a fast and simple way to detect locations of swirling flow in healthy and pathologic arteries. While aneurysms presented strong vortex cores (Fig.3 and (6)), weaker vortex cores were identified in the healthy aortic arch (Fig.2) and the carotid bifurcation (Fig.4). Automatic detection and visualization of vortex cores has a potential to help reveal and understand locations of swirling flow within 4D flow-sensitive MRI datasets.

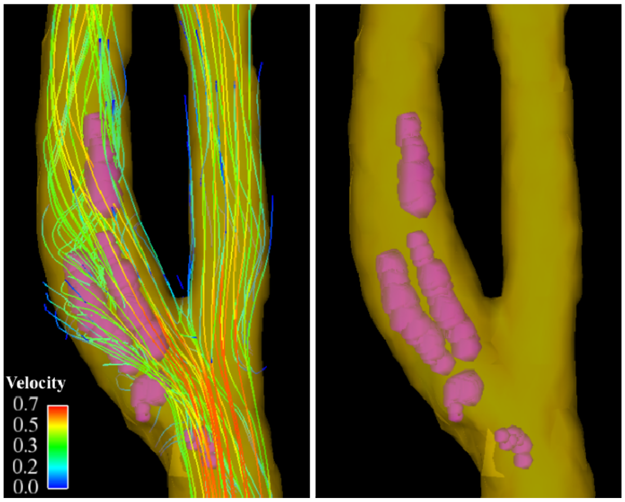


Fig.4: healthy volunteer right carotid bifurcation at peak systole: Streamlines (left) and vortex cores (right).

References: 1.Stein PD, et al. Circ Res 1974;35 2.Davies PF. Physiol Rev 1995;75 3.Kinlay S, et al. Curr Opin Lipidol 2001;12 4.Frydrychowicz A, et al. J Cardiovasc Magn Reson 2008;10 5.Wong KK, et al. Ann Biomed Eng 2009;37 6.Meckel S, et al. Neuroradiology 2008;50 7.Harloff A, et al. Magn Reson Med 2009;61 8.Kenwright D, et al. Proc. Visualization '97, 1997 9.Sujudi D, et al. Proc. AIAA, San Diego, CA; USA: 1995 10.Brandt E, et al. Proc. 9th ISMRM, 200111.Yang GZ, et al. Proc. 6th ISMRM, 1998 12.Markl M, et al. J Magn Reson Imaging 2007;25 13.Bock J, et al. Proc. 20th Conf MRA, Graz, Austria: 2008

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