3D quantification of Vorticity and Helicity from 4D flow data using finite element interpolations

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Target audience: Cardiologist, Radiologist, Medical Physics, Biomedical Engineers.

Purpose: Several methods have been proposed to analyze hemodynamic parameters from 4D flow data, however the quantification of these parameters from 4D flow data is usually done in 2D planes manually located along the vessel of interest, generating a dependency on the user that may lead to results that have low reproducibility. Some reports include the analysis of the vorticity and helicity to evaluate different flow patterns from 4D flow data, but most of these studies consist on a qualitative analysis [1-3]. Recently, it has been reported a quantitative method to calculate the helicity density or the relativity helicity density using 4D flow data[4], however this method is also based in the calculation of 2D planes. In this work we propose a novel method that integrates advanced image processing strategies and computational techniques based on finite element interpolations to obtain a 3D quantitative map of vorticity, helicity density and relativity helicity density derived from 4D flow data sets.

Methods: Based on the velocity field acquired from 4D flow, we developed a finite element based computational framework for obtaining continuous 3D maps of vorticity and helicity, using a similar finite element interpolation method previously published.[5] The process for creating the tetrahedral mesh from the 4D flow images consist in; generation of an angiography image,[6] the next step involve segmenting the lumen of the aorta applying an intensity threshold and separate the vessel of interest manually and finally create the tetrahedral mesh using the Matlab available toolbox (iso2mesh). The finite element analysis was development in the Python software, and for the visualization and analysis of the data we use the open source software Paraview. The 4D flow data was acquired in eighteen volunteers (14 males and 4 females, mean age 30 ± 5 years old), two patient with Tetralogy of Fallot (2 males, mean age 16.5 ± 5.2 years old), three patient with aortic coarctation (3 males, mean age 31 ± 4 years old), one patient with valve stenosis pulmonary (female, age 30), one patient with inter-auricular communication and pulmonary artery dilatation (male, age 25), and a thoracic phantom data in rest and with a coarctation of 9 mm. The data was acquired in a MR Phillips Achieva 1.5T, with an acquisition matrix of 106x106x54, reconstructed voxel size 2.16x2.16x2.5 mm, flip angle 6° and retrospective cardiac gating.

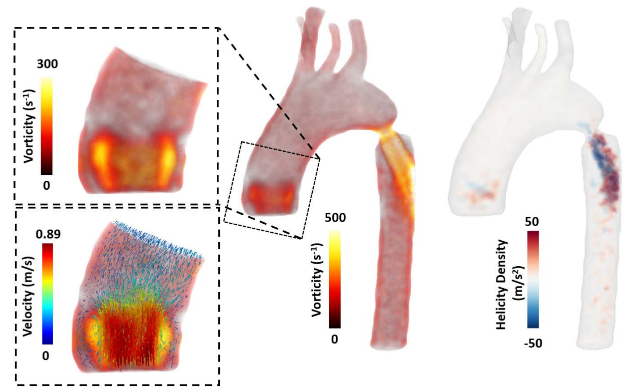

Fig 1. Vorticity and helicity density distribution in the phantom with a coarctation of 9mm.

Results: Figure 1 shows the 3D vorticity and helicity density map obtained in the phantom and in a TOF patient. The vorticity and helicity density values for the phantom were 400±290 s^{-1} and 71±80m/s^2. For the group of volunteer the vorticity values were 300±53s^{-1} and helicity density values 90±30m/s^2 in the aorta, for the pulmonary artery the vorticity values were 325±54s^{-1} and helicity density values 70±31m/s^2. The aorta of the group of patients with aortic coarctation showed vorticity and helicity density values of 480±32s^{-1} and 140±20m/s^2. In the aorta of patient with Tetralogy of Fallot the vorticity and helicity density values were 545±63s^{-1} and 70±14m/s^2, the pulmonary artery showed values of 730±180s^{-1} and 240±35m/s^2 for vorticity and helicity respectively. All relativity helicity density values are normalized between -1 to 1. The figure 2 and 3 shows the 3D maps of vorticity and helicity density and relativity helicity density for healthy and pathological data, for the aorta and pulmonary artery.

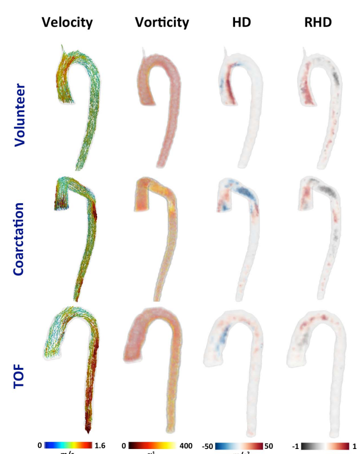

Fig 2. 3D maps of vorticity, helicity density and relativity helicity density, for the aorta of one volunteer, one patient with aortic coarctation and one patient with TOF

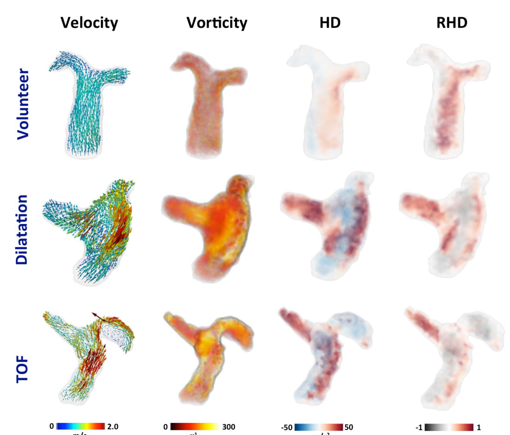

Fig 3. 3D maps of vorticity, helicity density and relativity helicity density, for the pulmonary artery of one volunteer, one patient with valve stenosis pulmonary and one patient with TOF

Discussion and Conclusion: We have proposed a novel method that allowed us to obtain 3D maps of vorticity and helicity related parameters derived from 4D flow using finite elements interpolation, which has been validate in data obtained from an aortic phantom, volunteers and patients. The 3D maps of vorticity and helocity allows us quantify the entire domain of interest without the need of reformatting the data to calculate these parameters.

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