A Novel 4D Flow Tool for Comprehensive Blood Flow Analysis

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Introduction: While the assessment of complex blood flows using phase contrast (PC) MRI is gaining attention, the accuracy of these measurements is of particular importance. It was recently demonstrated that uncorrected background phase offset errors can be a limitation for flow measurements [1]. Additionally, positioning of flow analysis planes and segmentation issues can further affect the reproducibility and accuracy of flow measurements. In this context, flow-sensitive 4D MRI allows retrospective flow evaluation at any vessel cross-section along an extracted centerline and can help the positioning of flow analysis planes. Typically, manual tools are used to localize vessel cross-sectional planes and define 2D lumen geometry on them for flow evaluation. This process is lengthy and inherently subjective and the presence of anatomical motion brings additional difficulty into such manual processing. In order to assess these issues of accuracy and time-consuming post-processing, we present our design of the 4DFlow analysis software package. This software package is a semi-automated tool that integrates background phase correction, velocity aliasing correction, semi-automated centerline tree detection and time-resolved 3D segmentation as well as advanced flow quantification and flow visualization.

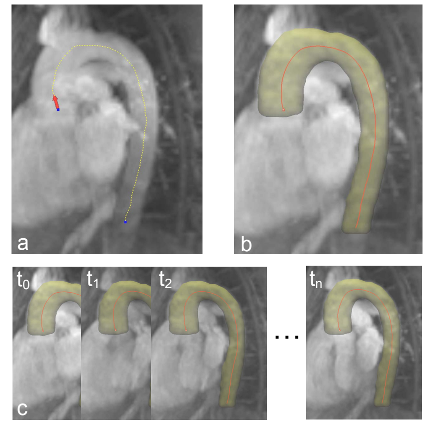

Figure 1: Extracted centerline between seed points (blue) (a) segmented lumen model (b) temporal propagation of the lumen model (c)

Materials and Methods: The vascular modeling method first detects a centerline tree representation between user-placed seeds (Fig 1a) and then extracts the lumen boundary using the detected centerlines (Fig 1b). The centerline extraction method is based on a minimal path detection algorithm which operates on a medialness map which is computed by contrast and scale independent filters using 2D multi-scale cross-sectional models and then integrated into a discrete optimization framework for centerline tracking [2]. The lumen extraction method is based on graph-cuts optimization technique using centerlines as input. It first constructs a tubular 3D grid graph in the vicinity of the input centerline with the integration of normalized boundary properties measured by multi-scale mean shift filters and then finds a smooth surface with globally optimum energy [3].

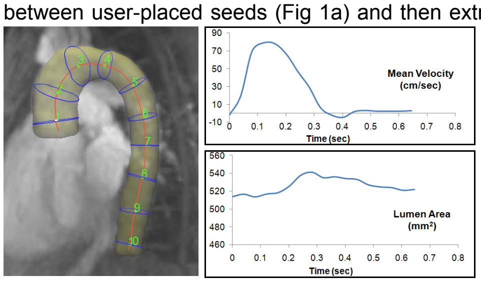

Figure 2: Analysis planes sampled along the centerline, and mean velocity and lumen area time-waveforms corresponding to a single plane.

After segmenting vessels from a temporal reference time frame, the extracted models are propagated across the entire time sequence using the displacement fields derived from a deformable registration technique in order to obtain a dynamic vascular model, including propagated centerlines and lumen boundary (Fig 1c). The deformable registration is a symmetric and inverse-consistent approach which delivers a high degree of accuracy and consistency of the deformation between individual time frames by maximizing the local cross-correlation [4]. The extracted 4D vascular models are then used to automatically or interactively position analysis planes at any location along the vascular centerline (Fig 2). Moreover, temporal correspondence of the analysis planes is achieved by tracking them using the displacement fields resulting in more accurate flow time-waveforms. Once the analysis planes are defined, quantification of flow parameters such as flow-rate, mean-velocity or peak-velocity is performed (Fig 2). In addition, advanced particle traces and streamline flow visualization are achieved in a timely and accurate manner by automated particle seeding and by incorporating time-resolved vascular models to restrict particle advection and particle generation (Fig 3). The software package was validated on 5 aortic datasets of healthy subjects and patients [5] (acquired at 3T, voxel size: 1.7x2.0x2.9 mm^3, temporal resolution: 40 ms). The quantitative values for the instantaneous mean velocity, lumen area and flow volume at eight analysis planes along the aorta were compared against the values from a previously reported quantification tool based on B-spline interpolation [6] (inter-method error). Furthermore, all data were reprocessed by a second independent observer to assess the inter-observer reproducibility.

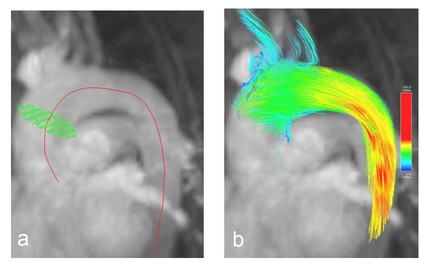

Figure 3: Automated particle seeding on a vessel cross-section (green points) (a) particle traces visualization (b)

Results: Each of the 5 datasets took less than 10 min including user operator time for the complete processing including data import, background phase and velocity aliasing corrections, 4D segmentation, advanced visualizations (vector field, streamlines, particle traces), quantitative analysis and export to a standard spreadsheet format. The inter-method and inter-observer errors (Table 1) were small and within 10% of the measured dimension for mean velocity, lumen area and flow volume.

	Average Value	Inter-Method Error	Inter-Observer Error
Mean Velocity (cm/s)	24.4	2.7 / 3.7	2.3 / 3.0
Lumen Area (mm^2)	476.1	44.0 / 43.7	44.2 / 31.0
Flow Volume (ml/cycle)	74.7	7.8 / 7.7	5.6 / 4.6

Table 1: Inter-method and inter-observer errors (mean / std dev). Errors are calculated from the absolute difference between instantaneous mean velocity, lumen area and flow volume.

Discussion: Thanks to advanced image processing techniques and complete workflow integration, the 4DFlow software package allows time-efficient, objective and accurate evaluation of 4D PC-MRI datasets. Complete data processing and analysis within 10 min were possible for which equivalent analysis using manual tools required hours. While the data in this study was analyzed at only 8 planes along the aorta (for comparison with the manual quantification tool), successful centerline detection allows performing quantification at any number of analysis planes along the aorta without additional processing work. Furthermore, good inter-method and inter-observer errors, within 10%, demonstrate the accuracy and reliability of the package while using 4D flow data with limited resolution and SNR. In a context where phase-contrast MRI remains of marginal clinical use, faster acquisition techniques combined with the integration, automatization and streamlining of the post-processing are key factors to enhance the accuracy, reproducibility and time-effectiveness of the technique and help bring it to the clinical routine. Future work should include validation in flow-phantoms, medium-sized vessels and vessel wall parameters such as wall shear stress. The limit of the 4D segmentation algorithm for vessels with abnormal geometry (e.g. large aneurysms, stenosis, dissection) should be evaluated and if needed, the software should also provide means for the manual correction.

References : 1) Gatehouse et. al., JCMR, 2010;12 2) Gulsun et. al., MICCAI, 2008; 602-611 3) Gulsun et. al., SPIE, 2010; 7625 4) Guetter et. al., ISBI, 2011; 590-593 5) Markl et al., JMRI, 2007;25 6) Stalder, et. al., MRM, 2008; 60