Novel strategies for patient-specific modelling of arteriovenous fistula for hemodialysis

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***Abstract*—Arteriovenous fistula (AVF) is the preferred vascular access for hemodialysis, but maintaining its patency is still challanging. Considerable research supports the role of local hemodynamic forces as triggering factors for the stenosis formation responsible for AVF failure. Longitudinal studies with repeated evaluations of local hemodynamic conditions are needed, therefore novel contrast-free MRI protocols should be designed to acquire reliable AVF patient-specific models suitable for computational fluid dynamics. In the present investigation we explored the feasibility of a novel contrast-free MRA protocol to acquire high-resolution images suitable for generation of patient-specific AVF models.**

***Keywords*—arteriovenous fistula, contrast-free MRI, computational fluid dynamics, hemodialysis.**

I. Introduction

NATIVE arteriovenous fistula (AVF) is the preferred vascular access for hemodialysis patients, but it still has high rate of failure due to vascular stenosis mainly caused by neointimal hyperplasia [1-2]. A growing body of evidence supports a key role of hemodynamics in stenosis formation [3-4], therefore longitudinal studies with repeated evaluations of local hemodynamic conditions and vascular changes over time are needed to investigate the relationship between disturbed flow and changes in vessel wall structure resulting in the formation of vascular stenosis.

These studies require reliable and non-invasive investigations to obtain patient-specific 3D AVF models to perform computational fluid dynamics (CFD) simulations. To avoid the use of gadolinium, due to the risk of inducing nephrotoxic fibrosis in end stage renal disease patients, novel protocols for contrast-free MR angiography should be designed. The purpose of our study was to explore the feasibility of a novel protocol for contrast-free MR angiography to investigate the hemodynamics inside AVF, coupling this imaging technique with high resolution CFD.

II. Matherials and Methods

A. MRA acquisitions

We acquired contrast-free MRA in a 78-year male with radio-cephalic side-to-end AVF. We performed 3D fast spin echo T1-weighted imaging with variable flip angles using CUBE T1 on 1.5T scanner (GE, Optima 450w GEM), with the following parameters: axial plane; 19ms echo time; 24ms echo-train length; 2mm slice thickness; 0.55x0.55x2.0mm voxel size. MRA acquisition was performed one week after AVF surgical creation.

B. 3D model reconstruction and mesh generation

Figure 1 shows the MRA-to-CFD pipeline of this study. AVF lumen with its limbs, the proximal artery (PA), distal artery (DA), juxta-anastomotic vein (JAV) and distal outflow vein (V), were digitally segmented using imageJ and patient-specific 3D surface was generated using the Vascular Modelling Toolkit (VMTK) [5]. A polygonal surface was generated by using a gradient-based level set followed by a marching cubes approach. Starting from the surface model, the internal volume was discretized using *foamyHexMesh* mesher, which is part of OpenFOAM 4 suite [6]. We obtained a mesh of 1,055,000 cells, with dominant-hexahedral core cells characterized by low orthogonality and well alignment to the vessel surface. Two thin boundary layers of cells were generated near the wall in order to capture the sharp gradients of velocity in this region.

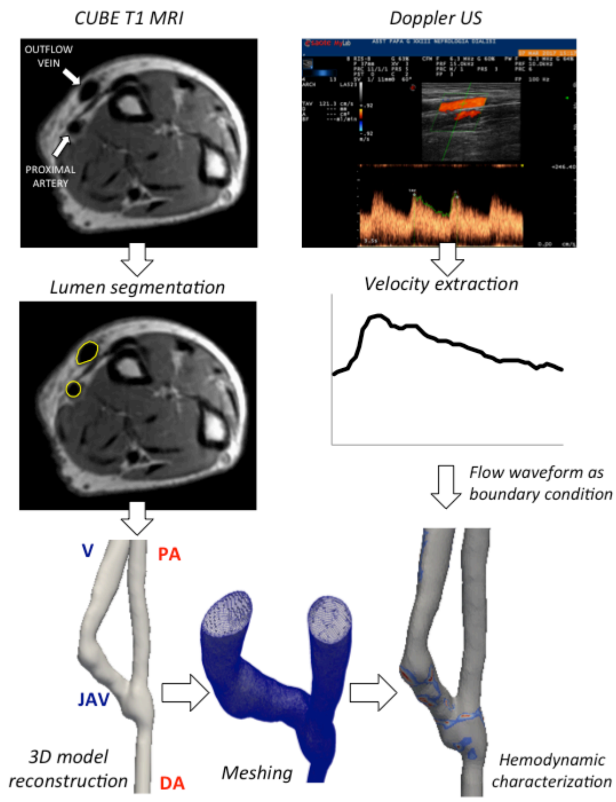

Figure 1.Workflow of the study from MRA acquisition to CFD analysis

C. *CFD simulations of blood flow*

Transient Navier-Stokes equations were solved by using OpenFoam, an open-source CFD-toolbox based on the finite volume method [6]. Volumetric flow waveforms obtained from US examinations were prescribed as boundary conditions at the inlet of the PA and at the outlet of the DA (*Figure 1*), while traction-free condition was set at the vein outflow. Vessel walls were assumed to be rigid and blood density equal to 1.05 g/cm3. Blood was modelled as patient-specific, non-Newtonian fluid using the Bird-Carreau rheological model. We used pimpleFoam, a transient OpenFOAM solver for incompressible flows, set with second order backward time integration scheme and set to operate in PISO mode only, resulting in very small time steps. This solver adjusts the time step based on a maximum Courant-Friedrichs-Lewy number, which we set to 1. Three complete cardiac cycles were solved to avoid start-up transients and only the third cycle was saved for post-processing in 1,000 equal time steps.

D. *Characterization of the flow*

We characterized the AVF blood flow phenotype using velocity streamlines and localized normalized helicity (LNH), a descriptor of changes in the direction of the rotation of flow. Post-processing of results was executed using the open-source data analysis and visualization application Paraview.

III. RESULTS

Contrast-free CUBE T1 yielded high-resolution images within a reasonable scan time of 5 to 10 minutes. Images were suitable for the segmentation of AVF lumen and reconstruction of patient-specific 3D model, that was used for high-resolution CFD analysis. Figure 2 shows velocity streamlines, representative of the peak-systolic time-point. Straight and parallel streamlines are present in the PA in AVF model, while secondary flows and complex vortices develop after the anastomosis in the JAV, and continue along the main stream of the venous segment.

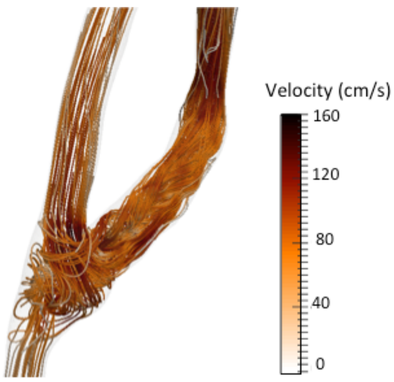

Figure 2. Velocity streamlines representative for the peak systolic time-point

Figure 3 shows that coherent highly helical flow structures, identified by LNH isosurfaces [7], originate in the anastomosis towards the vein with both clockwise and counter-clockwise rotation, as classified by the blue and red colour, respectively.

Figure 2. LNH isosurfaces representative for the peak-systolic-point

Results of the present investigation are in line with our previous observations conducted in four AVFs acquired using contrast-enhanced MRI [8].

IV. CONCLUSION

This novel contrast-free MRA protocol represents a feasible approach to obtain 3D AVF model that can be used for longitudinal investigations on the role of hemodynamics in AVF failure. The detailed study of blood flow field in anastomosed vessels at the patient-specific level may help to elucidate the role of hemodynamic in vascular remodelling and stenosis formation, with the final aim of improving AVF clinical outcome, both in terms of complications immediately after surgery and in terms of long-term patency. This achievement, besides entailing a significant reduction in medical costs, may significantly improve the quality of life of patients.

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