

An image-based and RBF mesh morphing CFD simulation for aTAA hemodynamic

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Abstract— It is well known that haemodynamic parameters, such as blood flow velocity, blood pressure and wall shear stress (WSS), are closely related with the pathophysiology of aortic diseases. However, the data regarding the formation and the progression of the bulge are still difficult to be obtained in a clinical setting. In this study, 3D surface models defined from healthy subjects and patients with ascending thoracic aorta aneurysms (aTAA), selected for surgical repair, have been generated. A representative shape model for both healthy and pathological groups has been identified. A morphing technique based on radial basis functions (RBF) has been applied to mould the shape relative to healthy patient into the representative shape of aTAA dataset so as to enable the parametric simulation of the aTAA formation. CFD simulations were performed by means of a finite volume solver using the mean boundary conditions obtained from three-dimensional (PC-MRI) acquisition.

Keywords—Ascending Aorta Aneurysm, Simulation, morphing, mesh parameterisation.

I. INTRODUCTION

IN the cardiovascular disease landscape the ascending thoracic aorta aneurysm (aTAA) is associated with a high morbidity and the rupture phenomena have a high mortality rate [1]. While aTAA diameter value is the conventional criterion for intervention, additional markers and parameters are needed for the diagnosis and monitoring of aTAA in view of preventing complications. Many researchers in the field of cardiovascular diseases have sought to identify good diagnostic and predictive biomarkers of aTAA [2]; however, as the mechanisms underlying aTAA development are not entirely clear, suitable markers have not been identified yet. It is well known that hemodynamic parameters, such as blood flow velocity, blood pressure and wall shear stress (WSS), are closely related with the pathophysiology of aortic diseases. Nevertheless, there is currently a significant lack of data able to characterize the formation and the progression of the bulge in a single subject as well as in a selected population. Recent studies have explored the capability to investigate a large “virtual population of patients” by applying stochastic approach into a finite element calculation environment [3]-[4]. In addition, in the last decade the coupling of medical imaging and computational fluid dynamics (CFD) techniques has contributed to enhance the comprehension of the aortic hemodynamics, with the possibility to obtain highly resolved blood flow patterns in anatomically realistic arterial models [5]-[6].

The aim of this work is to propose a novel computational approach built up by integrating patient specific images and flow data with RBF morphing techniques [7] into FE simulations. To showcase the consistency and effectiveness of the proposed approach, the effect of the shape of the bulge on the resulting flow patterns has been carried out.

II. METHODS

The overall study design is illustrated in Fig. 1. Briefly, given a set of aorta shapes reconstructed from 3D CT/MRI images, a statistical shape model was built through a pipeline of features extraction and registration.

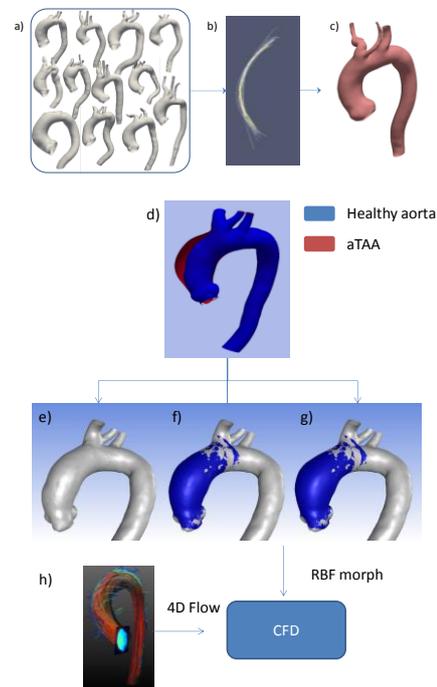


Fig. 1: Graphical representation of study workflow: example of a subgroup of segmented models (a); registration of ascending aorta centerlines (b); final SSG_A (c); change of aortic aneurysm from healthy to pathological model (d) and effect of shape modification on bulb shape by RBF Morph for initial (e), intermediate (f) and final shape (g); inlet and outlet flow conditions extraction from 4D flow data (h) used for CFD simulations.

Two datasets have been analyzed: a set of 5 healthy subjects and a set of 20 patients with aTAA selected for surgical repair. The images have been segmented and analyzed with VMTK (www.vmtk.org). For each patient, the

3D surface model has been then reconstructed (a). Features such as the centerlines, the section areas, the diameters, the curvature and the tortuosity values have been extracted and collected. Due to the interest in the ascending aneurysms, the registration process has been focused on this portion of the aorta (b). For each group, an averaged statistical shape geometry (SSG_H and SSG_A for healthy and aneurismatic geometry, respectively) has been defined (c).

The SSG_H has been used as starting geometry while the SSG_A has been used as target model (d). The RBF mesh morphing has been applied to modify SSG_H in order to obtain SSG_A by imposing changes to the vascular anatomy (e-g). In this study, we used a 4D PC-MRI in vivo dataset of the thoracic aorta of both healthy and pathological subjects. The representative inlet and outlet flow conditions were assumed for the CFD simulations, by using RBF mesh morphing technique. ANSYS Fluent has been used as Navier-Stokes CFD solver, the Fluent add on version of the RBF Morph software has been used for mesh morphing.

III. RESULTS

Figure 2 depicts the results of the morphological investigation performed on the two groups. While the maximum diameter and the tortuosity are suitable to distinguish between healthy and pathological subjects, the value of the mean curvature is not significantly different between the two groups.

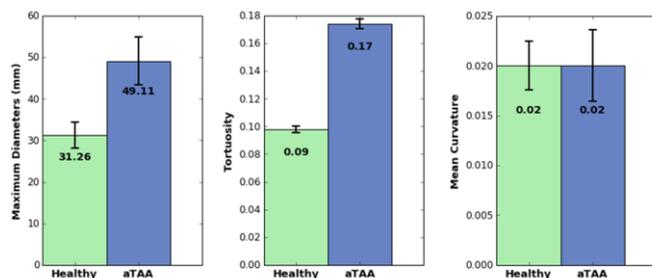


Fig. 2 Morphological results of both SSG_H to SSG_A with indication of the standard deviations.

The registration process has pointed out a close correlation among the ascending tract of the aorta geometries within each group, as indicated by the SD value. Figure 3 depicts preliminary results of CFD simulations obtained by Fluent with RBF mesh morphing technique (a-b) and from 4D PC-MRI data (c-d) for SSG_A and SSG_H . These results have shown that the turbulence of flow could be a further discretionary factor for aTAA identification. The flow velocity streamlines have revealed a greater turbulence for SSG_A than SSG_H . These simulations outcomes are in accordance with clinical results extracted from 4D PC-MRI dataset and with data in literature.

IV. CONCLUSION

In this work two specific issues have been considered. Firstly, the capability to define a representative morphology starting from a real patient population for both healthy and pathological subjects.

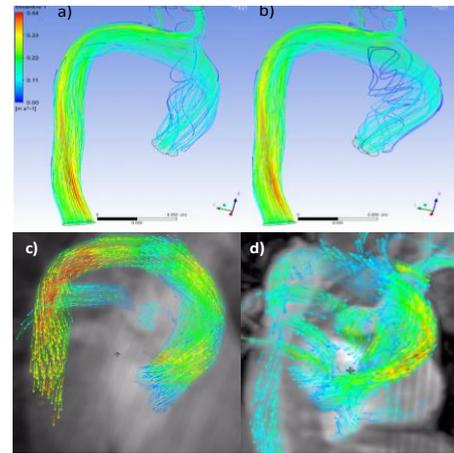


Fig. 3 Flow velocity streamlines for SSG_H (a) and SSG_A (b) extracted from CFD simulation; Flow velocity streamlines for SSG_H (c) and SSG_A (d) extracted from real 4D PC-MRI data.

This statistical shape analysis demonstrates its potential for discovering previously unknown 3D shape biomarkers in a complex anatomical shape population. Finally a novel RBF mesh morphing technique has been applied to study the aortic aneurysms evolution. Considering that the RBF mesh morphing is a meshless approach, this allows an easy management of hybrid meshes (nodal positions are updated regardless the kind of cell connected) and of partitioned meshes which are typically adopted in HPC simulations (preservation of interfaces is guaranteed as the field applied is a point function).

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