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Study of aortic dissections treatment. Segmentation, simulation and valiadation of surgical results

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Abstract. Nowadays, Computational Fluid Dynamics (CFD) it's seen as the new trend in the management of aortic pathologies. Together with visualization capabilities of cardiovascular magnetic resonance (CMR) and computed tomography (CT) imaging, real time segmentation (volumetric) models further used as meshes in Computational Fluid Dynamic supply to the clinicians an innovative and extensive decision-making system. In the present paper, we identified and analysed the clinical indicators (lumens diameters, fenestrated area and blood volume) monitored by clinicians to evaluate the patient' condition before and after the intervention. In order to achieve the targeted aims, we used CT scans as input data (segmented with MIMICS software) and output 3D models (3matic), further processed to mesh model in ANSYS software. Computational results validate the improved patient' condition, meaning the blood velocity tend to have values to normal flowing conditions. As a conclusion, the linear modification of velocity can be used in further investigations as an input value of pathology treatment

1 Introduction

Aortic dissection, characterized by separation of the aortic wall layers (initiated by dilatation of the aorta or high blood pressures) into true and false lumens (tearing the intima), may lead to serious complications including aortic rupture, myocardial ischemia, hypotension, shock, end organ ischemia and death [1]. Aortic dissection can be classified into Stanford type A dissection which involves the ascending aorta and Stanford type B dissection which involves the descending aorta [2].

The change of paradigm leaded by thoracic endovascular aortic repair (TEVAR) is based on moving the focus from treating only complications of Type B dissection towards preventing and treating those complications. This paradigm change has decrease the perioperative morbidity and mortality [5,6]. Even if there were reported and recognize huge advances in surgical and endovascular techniques, no consensus can be reported when the best treatment that should be applied to patients with dissection of the thoracoabdominal aorta is in discussion.

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The multilayer flow modulator (MFM - Cardiatis, Isnes, Belgium) stents appeared as a countermeasure to the traditional medical treatment and were designed to support complex endovascular repairs, and the main characteristics are: do not occlude branch arteries, can be overlapped to form complex structures, and even be custom built to match patient anatomy [6, 7]. The MFM stents are mesh constructs of cobalt-alloy wires interrelated in 5 layers, with the main characteristic of self-expanding, extremely flexible with high kinking and fatigue resistance and low total porosity. The device channels the blood flow, slow the flow vortices within aneurysm, and allow the blood to flow through native side branches. Moreover, with this device was used a minimally invasive intervention method.
The aims of this study are to analyse the remodelling of aorta after the intervention for aorta dissection using MFM devices using the software technologies existing on the market. The investigation is done using the MIMICS software that offer a robust segmentation toolbox for transform DICOM to 3D format (.stp, .stl, .iges). These virtual models (.stl) can be used for anatomical measurements or generation of meshes for finite element analysis. The investigation is focused on modifications of true and false lumen volume, and the increasing of true lumen diameters.

2 Software segmentation

2.1 Input data

All 16 patients (mean age 50 years, ± 13, 14 men) underwent an endovascular repair for aortic dissection with the multilayer flow modulator (MFM) stent between April 2014 and September 2018. They were followed prospectively, with regular visits to the clinic at 1 month, 3 months, 6 months and then yearly. At each follow-up visit data on adverse events, blood samples and high resolution CT scans are obtained. Events of interest are: death, re-intervention secondary to stent implantation, endo-leak or stent rupture, ischemic events (stroke, paraplegia, and acute kidney injury).

2.2 Data Acquisition

It was used a 16-row multi-slice scanner to acquire a CT scan of aorta of patients included in this investigation. The images have a resolution of 0.625 × 0.625mm and the inter-slice distance is 0.6 mm, covering the entire dissected aorta. The segmentation and surface reconstruction of aortic dissection were accomplished using the MIMICS (v20.0; Materialise, Leuven) software. Within MIMICS we perform a volumetric evaluation and, also, the measurement of true lumen diameters.
Detailed view of re-constructed aorta before and after the intervention are shown on **Table 1.** (anatomic geometries).

2.3 Volumetric evaluation

All medical images were processed using a segmentation protocol applied uniform on all imagines from computed tomography scans. The processing was performed within Mimics software (v20.0; Materialise, Leuven) and the results obtained are three-dimensional objects representing the false lumen and the true lumen, pre-operative and post-operative, for each of the 16 patients.

Table 1. Volume measurements of the true and false lumen pre- and post-op for 16 patients and False lumen volume index

	Pre-op				**Post-op**				**Latest Follow Up**			
Case	*TL Vol. cm^3*	*FL Vol. cm^3*	*Diam cm*	*FLI*	*TL Vol. cm^3*	*FL Vol. cm3*	*Diam cm*	*FLI*	*TL Vol. cm^3*	*FL Vol. cm^3*	*Diam cm*	*FLI*
1	33.29	77.05	0.44	2.31	68.29	31.40	1.61	0.46	93.32	0.68	1.79	0.01
2	63.40	256.40	0.96	4.04	106.71	177.17	2.25	1.66	187.08	2.53	3.08	0.01
3	100.17	148.53	0.60	1.48	92.60	133.30	0.64	1.44	170.38	87.97	2.67	0.52
4	96.33	138.99	0.87	1.44	194.11	67.27	2.20	0.35	177.95	86.43	2.11	0.49
5	71.09	299.80	0.60	4.22	136.24	248.98	2.06	1.83	106.40	286.74	1.80	2.69
6	NA	NA	NA	NA	231.74	109.62	2.34	0.47	246.75	61.39	2.32	0.25
7	13.34	2.99	2.33	0.22	26.96	5.59	2.39	0.21	28.49	4.66	2.40	0.16
8	83.18	412.04	0.65	4.95	182.56	344.43	1.80	1.89	130.76	244.89	1.84	1.87
9	26.21	218.30	0.16	8.33	195.93	56.86	2.56	0.29	250.10	211.64	2.71	0.85
10	36.61	299.17	0.20	8.17	138.12	216.88	1.72	1.57	166.44	210.70	1.75	1.27
11	131.00	351.68	0.68	2.68	244.19	267.25	2.17	1.09	250.65	259.73	2.13	1.04
12	19.77	218.37	0.15	11.05	112.84	138.95	1.87	1.23	131.08	124.24	1.80	0.95
13	168.00	212.53	0.76	1.27	188.16	126.07	1.95	0.67	235.22	122.60	2.22	0.52
14	131.50	202.73	0.35	1.54	178.75	134.08	2.19	0.75	227.40	2011.11	2.45	8.84
15	121.61	120.66	1.08	0.99	210.45	88.82	2.08	0.42	234.90	89.30	2.25	0.38
16	43.40	388.25	0.56	8.95	115.63	303.25	1.76	2.62	124.95	499.48	1.65	4.00

TL = True Lumen; FL = False Lumen; FLI = False Lumen Index

Table 1. shows the volume measurements for true lumen, false lumen and diameter before intervention, after intervention and at the latest follow up. The post intervention data represent the data just after the surgery.

The volume of true lumen was measure using the MIMICS software and the mean volume is 75.9 cm^3 (±47.72 cm^3) at pre-intervention and the mean volume after the intervention is 223.17 cm^3 (±115.19 cm^3) with a 199% mean increase of true lumen volume just after the intervention. Comparing the measurements of volumes of true lumen at the moment of latest follow up its observed that the mean volume increase at 172.62 cm^3 (±66.26 cm^3) with a 114% mean growth compared with pre-intervention moment. For all cases the volume of true lumen increased after the intervention apart from Case 3, that suffer a decrease of true lumen' volume by 8%. The maximum increase (748%) of true lumen volume was identified at Case 9.

The volume of false lumen records a mean decrease by 26% with a maximum decrease registered by case no. 9 (74%) and a minimum decrease by case no. 3 (10%), except the case 7, that registered an increase of false lumen volume with 87%.

For the 16 cases were obtained the volumetric geometries (see Fig) segmented from computed tomography scans preoperatively, postoperatively and at the latest follow up. We used the following image segmentation methods for each CT scan: setting-up the threshold (limits from 175 to 2604), then used "Region growing" functions to separate the masks.

Improvements of the geometry realized with “Edit mask”, in order to remove unnecessary regions, followed by “Dynamic region growing”, to establish existence of a single body in the future model. Before the calculation of the object, the operation “Crop mask” is used to obtain the output needed for the function “Calculate 3D object”.

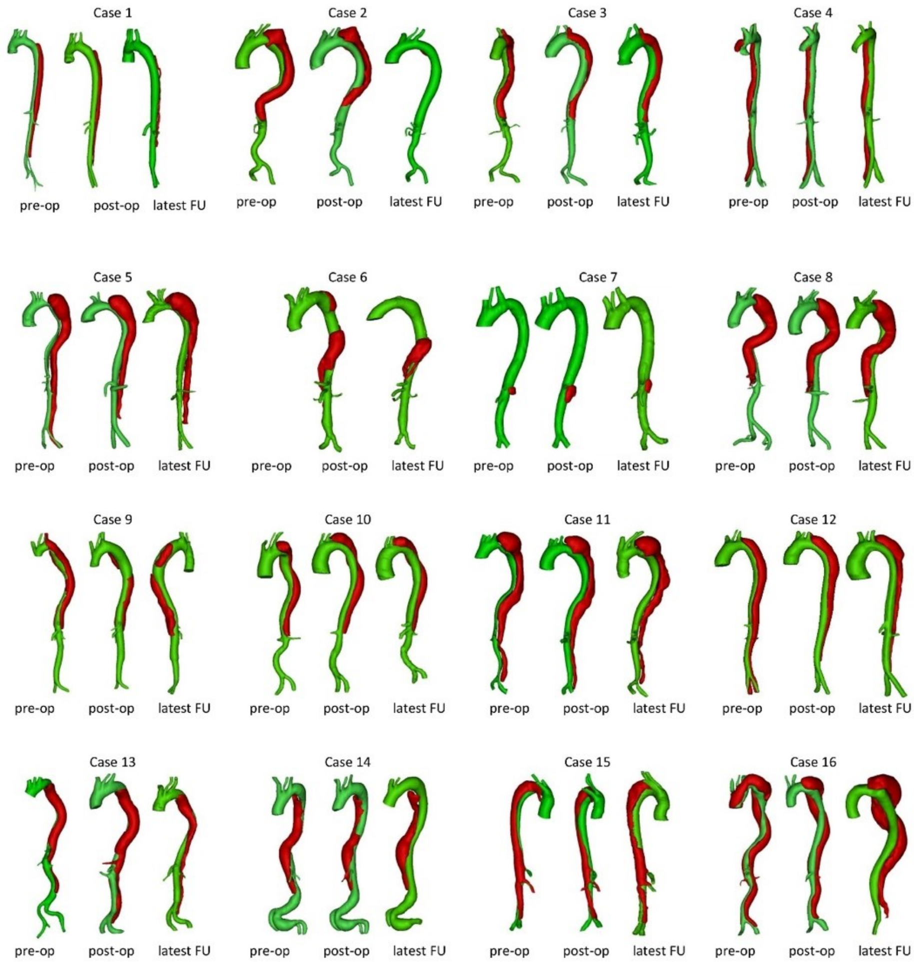

Fig 1. Volumetric geometries of 16 symptomatic chronic type B aortic dissections segmented from computed tomography scans preoperatively, postoperatively and at the latest follow up. All geometries comprise aortic branches and true and false lumens

False lumen volume index was calculated using the formula bellow, by dividing the false lumen volume to the volume of the true lumen,

$$false\ lumen\ volume\ index = \frac{false\ lumen\ volume}{true\ lumen\ volume} \tag{1}$$

After the intervention, there is a significantly decrease of false lumen volume index from a mean value of 4.11 (±3.44) to a mean value of 1.06 (±0.72).

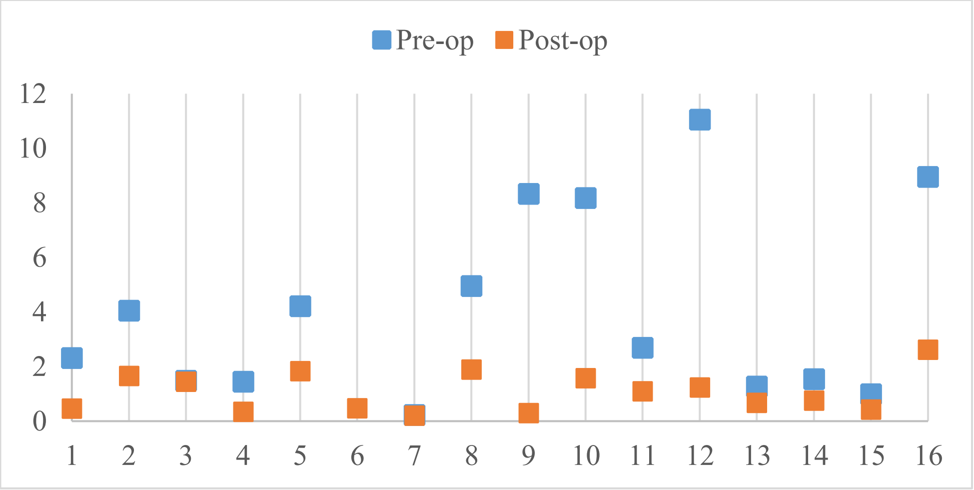

Fig 2. False Lumen Index drop

Figure Fig 2 shows the plot of the FLI for both states. Across the 16 cases, the FLI dropped for all situations, with a mean value of 27%. The case 9 and case 12 recorded the largest true lumen gain 748%, respectively 571% whereas the majority has a gain in the range of 92% to 266%. The false lumen volume was reduced by 36% the mean value in the group investigated. The decreasing trend can be observed at the all cases except cases 3 and 7, for these cases the difference is very small to be visible on the graphic (see Table 2). Based on the measurements made within MIMICS software the false lumen volume index decrease for postoperatively and continue decreasing based on the analysis made at the latest follow up for each case.

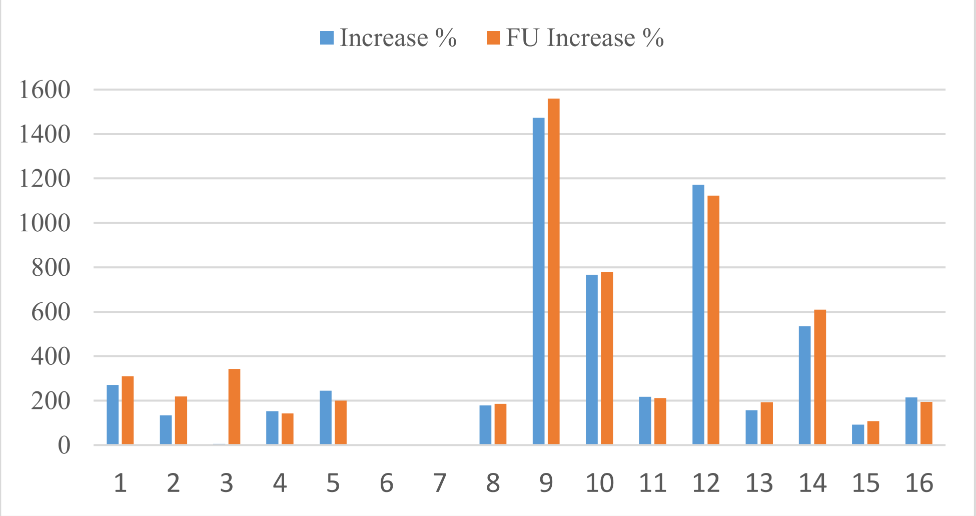

Fig 3. The increasing of true lumen diameters in percentage: postoperative and last follow-up compared with the preoperative moment

Analysing the FLI between the preoperatively and at the latest follow up moment can be observed that the decreasing is higher compared with the Figure 3, with the maximum regress registered for case 1 and a minimum regress registered at case 5.

Further, the diameter of the true lumen was measured at the maximum compression before and after the intervention and the mean value is 0.69 cm (±0.53 cm) preoperative and increase to 1.97 cm (±0.44 cm) postoperative, with a mean growth of 279%. And another growth is identified at the measurements of true lumen diameters during the latest follow up, the mean value is 2.18 cm (±0.41 cm) (see Fig 3). For the case 7 the increasing is very small and cannot be seen on the graphic (see Table 2).

3 Future works

In order to validate data analysed in clinical studies, for the future works ANSYS Fluent will be used. Assuming that the blood is a Newtonian fluid in large arteries [15], the principles of the motion of a three-dimensional fluid are the law of mass conservation and momentum. Precisely, the equation of continuity,

$$\frac{\partial u_i}{\partial x_i} = 0 \tag{2}$$

and the Navier-Stokes equations for an incompressible fluid,

$$\frac{\partial u_i}{\partial x_i} + u_j \frac{\partial u_i}{\partial x_i} = -\frac{1}{\rho}\frac{\partial p}{\partial x_i} + \frac{1}{\rho}\frac{\partial \tau_{ij}}{\partial x_j} \tag{3}$$

u_i (i=1, 2, 3) being the components of the velocity vector, p is the pressure, ρ is the fluid density.
Below is presented the analysis for Case 2 (Figure 4) and Case 9 (Figure 5), preoperatively, postoperatively and latest follow up with ANSYS Fluent.
Method parameters that were used are velocity 0.35 m/s^2 (inlet), viscosity 0.0035 $kg/m/s$, ρ 1060 kg/m^3, temperature 309.15 K, pressure 0 Pa (outlet).

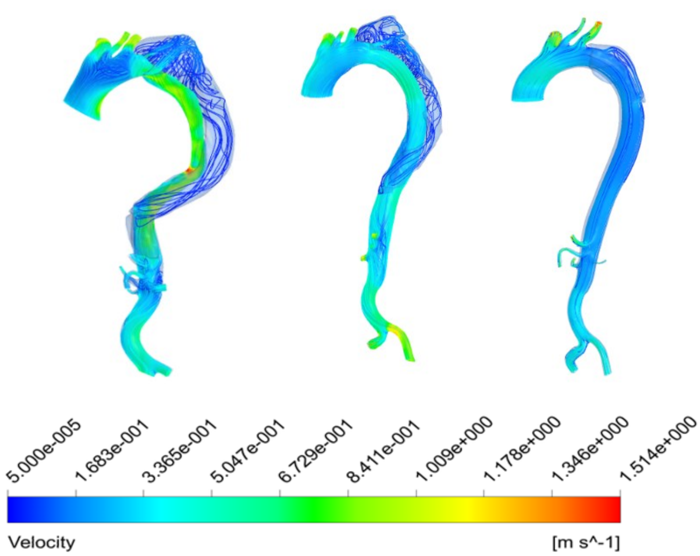

Fig 4. Velocity of preoperatively, postoperatively and latest follow up of Case 2

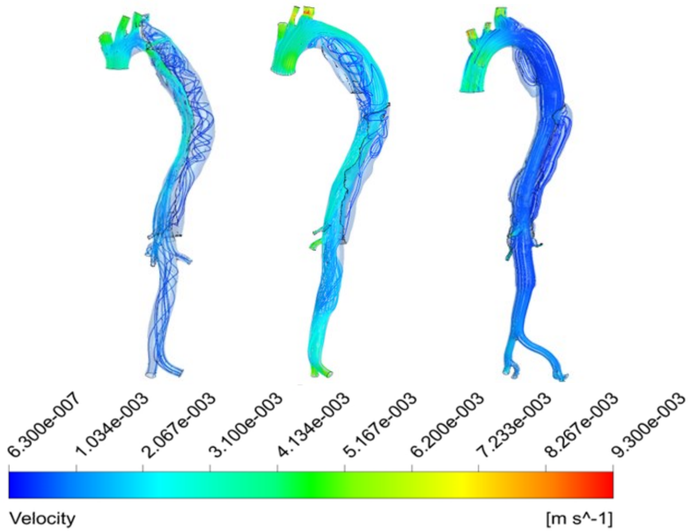

Fig 5. Velocity of preoperatively, postoperatively and latest follow up of Case 9

4 Conclusions

The aim of this paper was to analyse the measurements done with segmentation software (from Table 2) and identify and outline the direct results obtained after treatment of type B aortic dissection using Multilayer Flow Modulator devices.

The segmentation software was used by clinicians to analysis the cardiovascular physiology and compute parameters that cannot otherwise be obtained in a minimally-invasive way. Model accuracy is determined by model design and quality of input data.

While the quick segmentation, semi-automatic process and large segmentation parameters range is the main advantage in the usage of MIMICS software for extract the aorta in format 3D for an improved visualization, the manual and semi-automated segmentation methods require a high level of expertise and a significant time commitment on the part of the technician (engineer).

The results from usage of MIMICS software is represented by the exported in a 3D friendly format (.stp, .stl, .iges), thus physical models can provide the clinicians with a tactile experience and enable simulation of surgical or interventional procedures [14]. Velocity linearity of the CFD validate the improved patient' condition, meaning the blood velocity tend to have values to normal flowing conditions. The modification of velocity can be used in further investigations as an input value of pathology treatment. Also, another benefit of segmentation software such MIMICS is the exporting feature in 3-matic, used for optimizing the mesh for FEA, meaning further investigations such as wall stress, pressure of blood, turbulence inside the true and false lumen can be achieved.

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