Simulation of the fluid-structure interactions after balloon-angioplasty and stenting treatment in a stenosed arteriovenous fistula geometry

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Introduction

An arteriovenous fistula (AVF) is a permanent vascular access created by connecting a vein to an artery in patients that require hemodialysis [1]. The formation of stenosis occurs in 20% of the patients [2]; it is one of the major complications that affect the mid-long term AVF efficiency. The lesion can be treated endovascularly by balloon-angioplasty combined or not with stent deployment. The clinical efficacy of stenting in this very application has been debated since the late 80s [3]. The present objective is to model numerically the treatment of a stenosed AVF by balloon-angioplasty with and without subsequent stent deployment and to estimate the impact of the two treatment options on the fluid-structure interactions (FSI) in the AVF.

Materials and Methods

The patient-specific vascular geometry presents an 80% stenosis on the arterial side (figure 1). The vascular lumen has been segmented and reconstructed from medical images obtained at Polyclinique St. Côme (Compiègne, France) [4]. The vessel wall is meshed with a monolayer of shell elements. The fluid and solid meshes share the same nodes at the interface. The FSI simulations have been run for three cases: in the AVF geometry prior to any endovascular treatment (case A), after angioplasty (case B) and after angioplasty and stenting (case C).

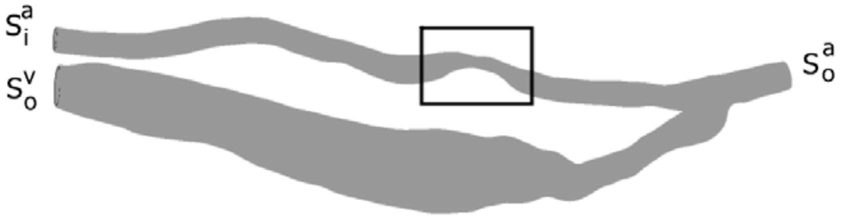

Figure 1. The patient-specific AVF geometry presents a stenosis on the brachial artery (see box). It is the geometry used for case A. S_i^a represents the arterial inlet, S_o^a the arterial outlet and S_o^v the venous outlet.

We simulate the treatment by balloon-angioplasty by inflating a balloon [5] positioned across the stenosis using Structural Mechanics (ANSYS, Inc.). Fixed boundary conditions are imposed at the extremities of the vascular geometry. The vessel after inflation presents a residual 20% stenosis, which is clinically realistic (figure 2). The fluid domain of the angioplasty-treated AVF has been remeshed to be used for the FSI simulation in cases B and C. In case C, the presence of the stent is modelled by imposing locally the equivalent stiffness of the stented arterial wall.

In order to take into account the inhomogeneity of the vessel wall, we differentiate the mechanical properties of different segments of the AVF vascular wall. The non-stenosed artery and the vein are assumed to follow the 3rd-order Yeoh constitutive law in the three cases. The mechanical behaviour has been differentiated at the stenosis: in cases A and B a plastic multi-linear hardening law is used in order to take into account the presence of the atherosclerotique plaque. In case C the “stented” region obeys to Hooke’s law to model the elastic behaviour of the stent. As for the fluid, we use Casson constitutive law to model the blood rheology.

The FSI simulations are run using the multi-physics environment provided by ANSYS (ANSYS, Inc.). The same flat, time-dependent velocity profile corresponding to the flow waveform measured on the patient by echo-Doppler is imposed at the inlet boundary of the fluid domain (S_i^a in figure 1) in the three cases: we had to neglect the influence of the endovascular treatments on the inlet arterial flow due to the lack of available data. Constant pressures are imposed at the arterial and venous outlets (S_o^v and S_o^a). They are previously evaluated in order to ensure the 70%-30% flow-split between S_o^v and S_o^a as well as an inlet pressure at section S_i^a in the range 55-65 mmHg in case A. For the solid domain, we set fixed constraints at the vasculature extremities but no mechanical constraint on the lateral vasculature wall. We assume a zero-stress state of the vessel at the beginning of the FSI simulation in all cases, since the fluid-structure interaction code does not allow the implementation of the initial stress state induced by the treatments in cases B and C.

In order to evaluate the equivalent stiffness of the stented artery, we model the stenting of the artery of the angioplasty-treated AVF using Structural Mechanics (ANSYS, Inc.). The stent that is deployed is a stainless steel, self-expanding Wallstent® (Boston Scientific; Natik, MA, USA), as shown in figure 3. We solve for the deformation of the stented artery imposing a ramped internal pressure in the lumen in an implicit structural simulation (Structural Mechanics, ANSYS, Inc.). The contact between the artery and the stent is solved using the Augmented Lagrange algorithm already implemented in Structural Mechanics (ANSYS, Inc.). We then run the same simulation for the non-stented artery and search for the mechanical properties of the stented region that lead to the same deformation.

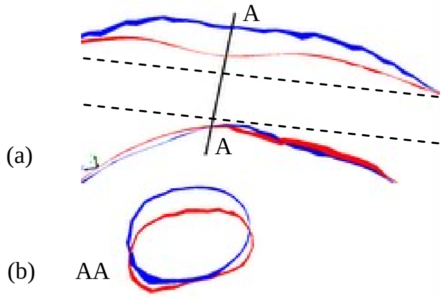

Figure 2. Cross-section of the stenosis region before (red) and after (blue) balloon-angioplasty in the longitudinal axial plane of the vessel (a) and in plane AA (b). The initial position of the balloon before inflation is indicated by the dotted lines.

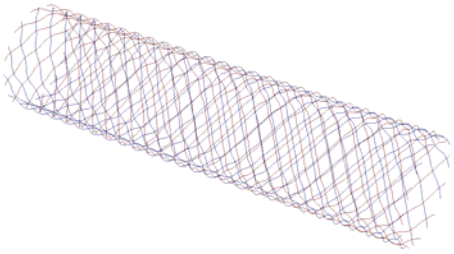

Figure 3. The wirestent Wallstent® (Boston Scientific) is reconstructed using the software Pyformex (http://pyformex.berlios.de/).

Results and Discussion

The structural simulation provides a value of the equivalent stiffness in the stented artery, which is nearly 10 times higher than the initial arterial stiffness. The Wallstent® therefore increases locally the equivalent stiffness of the vessel after deployment. The change in mechanical properties results in a local increase in the wall internal stresses in the “stented” region, if one compares results of the FSI simulation of case C with those of case B. No significant differences are otherwise observed for the wall internal stresses inside the vein among the three cases.

In the non-treated case (case A), we observe a venous flow rate, which falls in the range 500-1000 $\text{ml}\cdot\text{min}^{-1}$: the fistula is therefore functional for hemodialysis [2]. Even though the present stenosis does not affect substantially the flow rate, it leads to a non-physiological pressure drop. The time-averaged pressure drop across the stenosis is 8 mmHg, which is above the clinical treatment criteria (5 mmHg) [6]. After treatment, the stenosis pressure drop is restored to physiological values both in cases B and C (2.7 mmHg). It proves that the two treatment options improve the AVF efficiency in a similar way.

Additionally, they both modify the flow locally in the treated region, but have little impact far away from it. This can be seen in Figure 3, which compares the streamlines at peak systole before and after angioplasty. Hardly any difference can be found on the overall hemodynamics between cases B and C. It indicates that changing the wall mechanical behaviour by stenting does not improve further the efficiency of the balloon-treated AVF from a hemodynamic point of view. The treatment of the present arterial stenosis does not significantly modify neither the venous outflow not the flow in the enlarged portion of the cephalic vein. The latter is still subjected to low wall shear stresses, so that neither angioplasty nor stenting prevent the risk of atherosclerotic plaque formation [7].

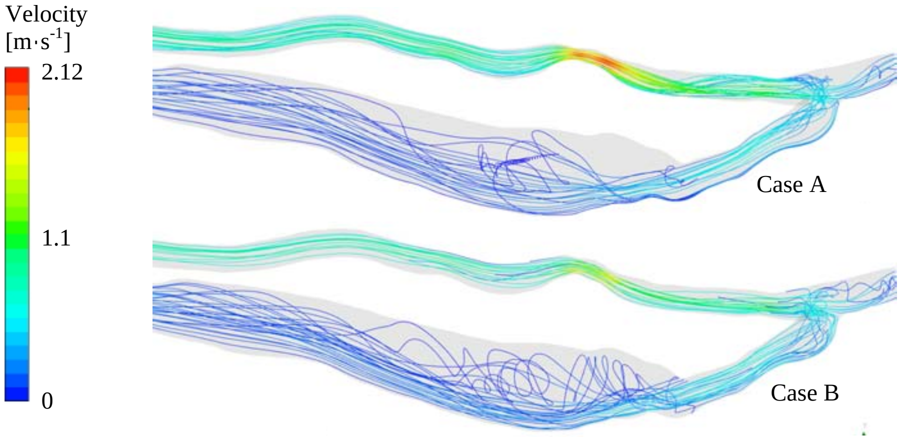

Figure 3: Comparison of the velocity streamlines at peak systole in cases A and B.

Conclusion

The originality of this work is to simulate two endovascular treatments of stenosed lesions (angioplasty with/without stenting) in an implicit structural simulation and to evaluate the equivalent mechanical properties to correctly model deformation of the "stented" region. The analysis of the fluid-structure interactions enables the quantification of the direct effects of the two endovascular treatments on the AVF efficiency. Hemodynamic results show that the two treatments (cases B and C) are equivalent. This is coherent with clinical evidence which shows that the primary patency of a stenosed AVF is similar for both angioplasty and angioplasty + stenting [2,8]. Still the stenting procedure decreases the remodelling of the vessel and can therefore maintain the treatment efficiency in the mid-long term [8].

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