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Sofia Loffredo, Carine Guivier-Curien, Valerie Deplano. Influence of the presence of a porous thrombus on hemodynamics in a CFD model of a descending thoracic aneurysm. Congrès de la société de biomécanique, Oct 2021, St Etienne, France. pp.S189-S191, 10.1080/10255842.2021.1978758 . hal-03428700

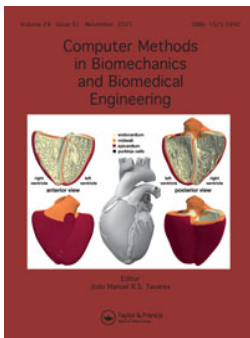
HAL Id: hal-03428700

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Submitted on 27 Nov 2021

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Computer Methods in Biomechanics and Biomedical Engineering

ISSN: (Print) (Online) Journal homepage: <https://www.tandfonline.com/loi/gcmb20>

ABSTRACTS 46^{ème} Congrès Société Biomécanique

To cite this article: (2021) ABSTRACTS 46^{ème} Congrès Société Biomécanique, Computer Methods in Biomechanics and Biomedical Engineering, 24:sup1, S1-S325, DOI: [10.1080/10255842.2021.1978758](https://doi.org/10.1080/10255842.2021.1978758)

To link to this article: <https://doi.org/10.1080/10255842.2021.1978758>



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Published online: 26 Nov 2021.



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Influence of the presence of a porous thrombus on hemodynamics in a CFD model of a descending thoracic aneurysm

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1. Introduction

A descending thoracic aneurysm (DTA) is a local and permanent enlargement of the thoracic aorta caused by pathological changes in the anatomy and function of the arterial wall. Within aortic aneurysm sacs, intraluminal thrombus (ILT) can develop. ILT is a 3D fibrin structure comprised of blood cells, platelets, blood proteins, and cellular debris, leading to a network of canaliculi along its entire thickness and making it permeable to fluids (Adolph 1997). From one hand, the hemodynamics in the aneurysmal aorta is hypothesized to be a key contributor to the formation and growth of ILT. On the other hand, the protective or deleterious role of ILT in the pathology evolution is still under debate. To tackle all these issues, it is thus essential to include ILT in Computational Fluid Dynamics (CFD) models of aortic aneurysms. However, either CFD models currently take into account ILT through only a reduction in aorta diameter (Qiu 2019) or its influence is modeled as a solid material with a specific mechanical behaviour to study fluid-structure interactions (Bluestein 2009). Only a few CFD models include it through a porous (Raptis 2016) or poroelastic (Toungara 2013) medium but often in idealized geometries of abdominal aneurysms. The objectives of this study are to propose a CFD model of DTA including a porous medium mimicking the ILT presence, to investigate its influence on hemodynamics and the relevance of integrating such a porous model in future models.

2. Methods

2.1. Geometrical and physical models

Two geometrical models were proposed. The first one was an idealized 2D axisymmetric model (Figure 1A). The second one was a 3D model built from CT-angiograms of a 72-year-old man with DTA. To focus on thrombus, only the 3D geometry of the aneurysmal zone is modelled (Figure 1C). In

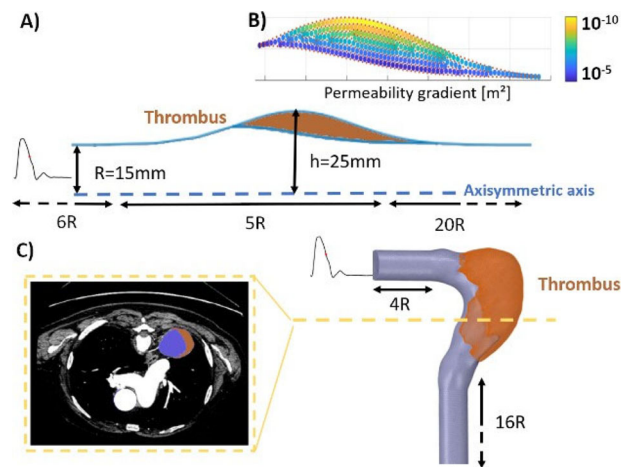


Figure 1. R is the radius of inlet tube A) Idealized 2D axisymmetric model. B) Illustration of permeability gradient. C) 3D model.

both models, extra-straight tubes were added upstream and downstream to ensure fully developed flow conditions. Meshes were refined in the boundary layer. At the inlet of both models, a fully developed unsteady velocity profile (Womersley solution) was implemented from a thoracic aorta flow rate described by Olufsen et al. (2000). At the outlet, an outflow condition was imposed. Walls were rigid with a no-slip condition.

Flow was assumed to be laminar. The blood was modelled as an incompressible fluid with Newtonian behaviour ($\rho = 1060 \text{ kg/m}^3$ and $\mu = 4.10^{-3} \text{ Pa}\cdot\text{s}$). Cardiac period was 1s. The mean Reynolds number was 1450.

2.2. Porous model of thrombus

Thrombus is modelled as a porous medium governed by the Darcy's law including as a source term in Navier-Stokes equations. To investigate the influence of permeability k on fluid flow, a parametric study was performed within the 2D axisymmetric geometry. Constant values were set to $k = 10^{-7}, 10^{-9}, 10^{-12} \text{ m}^2$ and a gradient of permeability which represents the heterogeneous aspect of ILT, was defined between 10^{-5} m^2 and 10^{-10} m^2 (the exponent of the permeability changes linearly through the thrombus depth, Figure 1B). A case with no ILT was developed for comparison. To avoid an excessive computational time, only one constant value was tested in the 3D model, corresponding to $k = 10^{-9} \text{ m}^2$.

All simulations were performed on Ansys Fluent Software. Convergence was reached at the third cycle and results presented are from this cycle.

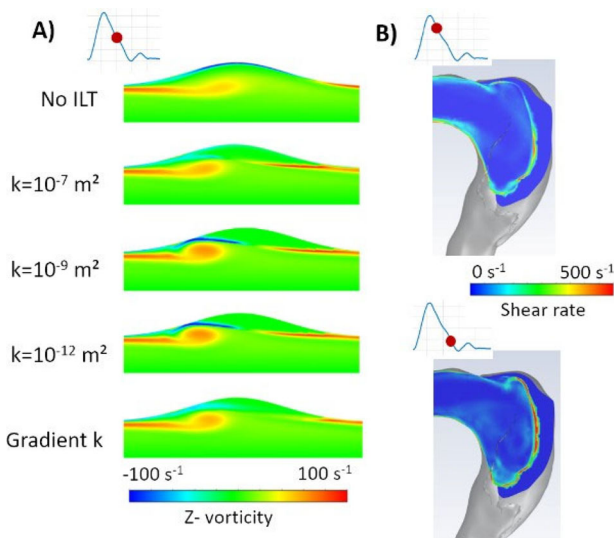


Figure 2. A) Z-vorticity map in 2D axisymmetric idealized model. B) Contours of shear rate in 3D model in a plane intersecting the aneurysm during deceleration.

3. Results and discussion

3.1. Axisymmetric models

The hemodynamics is studied through the description of velocity and vorticity fields. As expected, the widening of the cross-section leads to the formation of a jet flow with maximum velocity values at systolic peak and the appearance of recirculating zones that enlarge during diastole. These flow patterns lead to the occurrence of a vortex that detached from the aneurysm neck and moves toward downstream during deceleration (trace of vortex shown on Z-vorticity map in Figure 2A). The change in k causes noticeable differences on vorticity patterns between $k=10^{-7}$ and 10^{-9} m^2 , while between $k=10^{-9} \text{ m}^2$ and 10^{-12} m^2 , changes are minimal. In comparison, the results obtained with a gradient of permeability show a similar trend to the higher permeability value ($k=10^{-7} \text{ m}^2$). It is worth noticing that without ILT, the low wall shear stress values currently known to be involved in aortic remodelling in the aneurysm are overestimated. The velocities in the ILT are a function of the permeability value; for the minimal velocity values, there is a 4 orders of magnitude difference between those recorded for the highest permeability (1.10^{-5} m/s) versus the lowest one (1.10^{-9} m/s).

The permeability $k=10^{-9} \text{ m}^2$ seems to be a threshold value below it no substantial changes are observed. This value was chosen for the 3D model.

3.2. Three-dimensional geometrical model

As previously observed in the 2D axisymmetric model and confirmed in the 3D model, the vortex that develops at the aneurysmal neck does not penetrate the

porous ILT. Its disaggregation in the downstream arterial lumen combined with low time average wall shear stress could influence the expansion of thrombus formation downstream. At the interface between lumen and thrombus, shear rate values higher than 500 s^{-1} are observed, especially during deceleration (Figure 2B). Such values are reported to be high enough to compromise the thrombus integrity and allow piece of clot to detach (Xu 2017).

4. Conclusions

The integration of a porous medium to model the thrombus influences hemodynamics and observations are linked to its permeability value. Thrombus permeability is often referred to 10^{-15} m^2 . However, a wide range of values can be also found in literature, from 10^{-18} m^2 (Muthard 2012) to 10^{-7} m^2 (Raptis 2016). It is undoubtedly due to the heterogeneity of the material composed of 3 distinct layers and its age at the time of experimental permeability assessment. A gradient of permeability seems therefore to be more realistic to represent the complex structure of ILT. Moreover, its mechanical behaviour must be taken into account through a poro-elastic model for instance. So, *in vitro* experiments are currently ongoing on thrombus characterization to both measure its actual permeability and define a relevant elastic modulus.

Disclosure statement

No potential conflict of interest was reported by the authors.

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KEYWORDS Numerical modelling; thrombus; thoracic aneurysm; hemodynamics; porous medium

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