HEMODYNAMIC PREDICTION OF THROMBUS-PRONE REGIONS IN ABDOMINAL AORTIC ANEURYSMS

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INTRODUCTION
Intraluminal thrombus (ILT) is present in almost all abdominal aortic aneurysms (AAAs), with several studies trying to clarify if it increases or decreases the risk of rupture: it increases local proteolytic activity and causes wall hypoxia leading to wall weakening, but it also seems to act as a mechanical buffer against wall stress. In the meantime, the prediction of its growth might be of value, as clinical studies have demonstrated that ILT growth might indicate increased AAA rupture risk [1].

Thrombus formation and growth is a complicated process, with several biological and hemodynamic factors participating in a dynamic cascade. The formation is initiated by activation of platelets, which is determined by a combination of factors including high shear stress and time exposure to such stresses. Activated platelets accumulate next in recirculation and stagnation regions of the flow field, where they attach usually to the non-endothelialized surface, where low WSS and high residence time promote their adherence. This dynamic and multifactorial process of thrombus formation and evolution makes it difficult to model and predict its deposition pattern.

In an effort to study the hemodynamic induction of ILT formation, the Lagrangian approach is usually considered for the evaluation of coherent vortex formation (that affect platelet activation), a process that requires substantial computational efforts. However, since many studies show that AAAs possess the necessary hemodynamic conditions for coagulation and activation of platelets, the AAA sac is most likely filled with activated platelets ready to attach to a thrombogenic surface if the hemodynamic conditions are favorable. Therefore, near-wall hemodynamics is most probably the major determinant of ILT deposition. Our hypothesis is that with a statistically sufficient patient cohort, a co-mapping of flow conditions at the AAA wall with the information of ILT deposition distribution will allow the construction of a statistical model that will predict thrombus-prone regions.

In the present study we compute the time averaged wall shear stress (TAWSS) distribution in two patient specific AAAs that were thrombus-free at the first scan. The luminal surface is then divided into patches. In each patch the TAWSSs and ILT thickness are averaged. A logistic regression is then performed to test the statistical significance of the association between hemodynamics and thrombus location. Although the patient cohort is small, this study demonstrates proof-of-principle for a more extensive ongoing follow-up study.

METHODS
Data Acquisition
Two CT scans of AAAs (and their follow-ups) were obtained. The 3D lumen and external wall surface of the sac were reconstructed with ITK-SNAP and smoothed in vascular modeling tool kit (vmtk). The AAA surfaces were co-registered using the aorta at the level of the renal arteries (≥ 5 mm) and the aortic/renal bifurcations as registration features. The ILT thickness was measured at the follow-up AAA model as the distance between lumen and external surface.

Meshing and Computational Fluid Mechanics
Flow extensions were added to the luminal surface of the first scan, and a full hexahedral mesh was constructed using ANSA (BETA CAE Systems S.A., Greece) consisting of approximately 800,000 elements. In order to account for the shear thinning properties of blood, the Herschel-Bulkley viscosity model was considered. Simulations were performed using Fluent (ANSYS Inc.) with default convergence criteria set to 10⁻³. A pulsatile profile was prescribed at the inlet with $Re_{max}=330$ and $Re_{min}=1800$, and results were collected after all transient effects were washed out. The TAWSS was computed...
and its distribution was mapped on the surface.

**Surface Patching**

As the shape and size of AAA change with time, a methodology was needed in order to identify the corresponding regions between follow-up images. For this purpose the “mapping and patching” algorithm implemented in vmtk was used. In brief, since the aorta is topologically equivalent to a cylinder, it can be mapped onto a rectangular parametric space that allows the comparisons between different models. The surface of the aorta is divided into a number of contiguous rectangular regions on the surface over which the quantities of interest are averaged. The important feature of the methodology is that the location of each patch is preserved despite the variability in local surface geometry, allowing for the direct comparison of each patch (and its quantities) between the first and the follow-up scan. The luminal surface of the first scan (with the hemodynamics information) and the luminal surface of the second scan (with the thrombus thickness information) were patched as seen in Figure 1B.

**Statistics**

For each patch, the mean TAWSS value was obtained while the subsequent ILT deposition was recorded as a dichotomous variable. Median and range of TAWSS values for the AAA regions was recorded while a Mann-Whitney test was used to compare TAWSS between thrombosed and non-thrombosed AAA regions. Moreover, a logistic regression analysis was applied to test the statistical significance of the association between TAWSS and thrombus location.

**RESULTS**

Thrombus deposition was observed to negatively correlate with TAWSS values. In Figure 1, the initial hemodynamics and ILT deposition at follow-up, is presented before and after surface patching. For the purpose of illustration, the inverse of time-averaged WSS is shown, which is also proportional to the relative residence time.

Median TAWSS of AAs under evaluation was 0.14 Pa (Range: 0.02-0.42). Regarding non-thrombosed aneurysm regions median WSS was 0.14 Pa (Range: 0.03-0.42), while for those with subsequent ILT deposition respective values were 0.03 Pa (Range: 0.02-0.21). This difference was statistically significant (P-value=0.001).

The logistic regression demonstrated that there existed a significant association of low TAWSS values with subsequent ILT deposition. Specifically, there was a 0.115 (95% CI: 0.028-0.472, P-value=0.03) odds ratio of a patch to develop thrombus deposition for each 0.1 Pa decrease in TAWSS values. In other words the odds of a location developing thrombus, increased by almost 9-fold with each 0.1 Pa of TAWSS decrease.

**DISCUSSION**

This study investigated the relationship between a hemodynamic index and ILT deposition, and a relation was determined between areas with low WSS and thrombus deposition at a follow-up image.

While the multifactorial nature of thrombus formation has triggered a large number of researchers to study and model the hemodynamic induction of thrombus formation, there is only one recent study to our knowledge that investigated how well near-wall hemodynamics correlates with thrombus formation in patient-specific data sets [2]. However, in this study, the authors correlated the thickness change of ILT, not just the deposition of thrombus as a binary variable, with hemodynamics, and only oscillatory shear index was found to significantly correlate with thrombus growth. They conclude that for the prediction of thrombus growth, biochemical reactions with transport should also be considered besides hemodynamics. While the growth may be more difficult to model and predict, the deposition or no deposition of ILT in a thrombus-free small aneurysm can potentially be predicted by near-wall hemodynamics alone. Such a study has already been performed in intracranial aneurysms and a significant correlation was observed between regions of either low WSS or increased residence time, and thrombus deposition at follow up [3].

![Figure 1. Initial hemodynamics (1) and ILT deposition at follow up (2) A. Before patching, B. After patching.](image)

**REFERENCES**