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Correlation of Black Blood MRI with Image-Based Blood Flow Simulations in Intracranial Aneurysms

Abstract: Intracranial aneurysms (IA) is not-uncommon pathology of cerebral vessels. Vessel wall magnetic resonance imaging can visualize the vascular walls of IAs. In some aneurysms, the wall-adjacent and a luminal hyperintense signal was detected. The signal was attributed to the inflammation and specific hemodynamic features of aneurysms. But, up to now, the studies investigating luminal enhancement combined with flow analysis are limited. Therefore, in this study, investigation of the luminal enhancement is further carried out by comparison to computational fluid dynamics. The latter provides the possibility of calculating hemodynamic parameters, which can give information such as velocity, pressure, and shear stress fields throughout a heart cycle. The data of the IAs is specific to each patient and builds the basis for the enhancement analysis and simulations. Specific hemodynamic parameters like kinetic energy and vortex formation evaluated in the simulations show a dependency to signal suppression recorded with vessel wall magnetic resonance imaging.

Keywords: Computational fluid dynamics, Black blood magnetic resonance imaging, hemodynamics, intracranial aneurysm

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1 Introduction

As medical imaging techniques improve, the possibility to visualize vessels and pathologies in the human body gets better too. Intracranial aneurysms (IA) are a pathology of cerebral vessel walls, with an estimated incidence in the adult population of ~3% [1]. Aneurysm rupture can have fatal results like subarachnoid hemorrhage, and the current treatment options of IAs involve complications. The individual rupture risk analysis is therefore highly important.

Different medical imaging techniques are used to analyse the vessel structure and detect aneurysm occurrence [2]. One of these techniques is vessel wall magnetic resonance imaging, which can visualize the vessel wall by suppressing the blood in the vessel lumen (black blood MRI – BB MRI). Recently, it was found that some aneurysm walls are characterized by hyper intense signals on post-contrast BB MRI, and some not. Such wall enhancement was attributed to inflammatory processes [4] and linked to a higher risk of aneurysm rupture [5]. In addition, the comparison to hemodynamic parameters calculated in computational fluid dynamic (CFD) models represented a relation between signal enhancement and slow flow as well as wall shear stress [6,7].

To get further insights and find out more about the relation between BB MRI signal intensity (SI) and the underlying flow, the quantitative analysis has been progressed by comparing hemodynamic parameters to the signal intensity measurements.

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2 Material and Methods

2.1 Material

In this study, three patient-specific IA models from three patients with age over 50 years were analysed. The models differ in position, shape, and size to serve as a basis for comparison. Model 1 has a size of (38x28) mm², model 2 of (36x25) mm², and model 3 is the smallest model with (12x10) mm². The IA models were produced based on patient 3D rotational angiography (3D RA, Allura XperFD 20/10, Philips, Best, The Netherlands). Segmented virtual vascular lumen was used for CFD simulations [4].

Table 1: Three-dimensional segmentation results of the patient-specific intracranial aneurysms and related disclosures. For better visibility, the models are shown with a similar size. However, the models possess different dimensions

Model	Shape	Size in mm ²	Patient data	Inflow rates in ml/min
1)		(38 x 28)	58 years, female	Low: 160; high: 266
2)		(36 x 25)	57 years, female	Low: 203; high: 307
3)		(12 x 10)	65 years, male	Low: 208; high: 311

An outer layer was added to the vascular lumen; next, the resulting flow models were 3D printed, placed in an MRI system (Ingenia CX, R5 V6.1, Philips Healthcare, Best, Netherland), and supplied with a pulsatile flow. Models

underwent BB MRI protocol yielding a set of 3D images visualizing the IA lumen. The signal appears black when the signal suppression was successful.

2.2 Methods

The flow inside the IAs were analysed by CFD analysis. STAR-CCM+ 14.04 (Siemens Product Lifecycle Management Software Inc., Plato, TX, USA) was used to perform the simulations. In this study, the focus is on the comparison of the CFD results to the BB SI.

2.2.1 Hemodynamic simulations

The inlet boundary conditions for the simulations were set to a low and a high inflow rate depending on the aneurysmal geometry. At the outlets, the time-varying pressure was measured prior to MRI experiments, which were performed previous to this study [4]. The resulting curves were set as boundary conditions in the simulations. Furthermore, a blood mimicking fluid was used [4].

Hemodynamic parameters evaluated during the simulations were velocity, kinetic energy (KE), vorticity, λ_2 , and Q-criterion, as well as flow rate and the individual velocity components. Mapping the hemodynamic parameters onto the BB SI values enables a point-to-point evaluation of these metrics. These steps as well as the qualitative evaluation were carried out in EnSight v10.2 (ANSYS Inc., Canonsburg, PA, USA).

2.2.2 Statistical analysis

MATLAB R2020b (MathWork, USA) was used for the analysis of the data. With a point-wise comparison, the correlation coefficient between SI and the specific hemodynamic parameters was calculated. To generalize the BB data, the signal intensity was grouped into 10 clusters based on SI from lowest to highest. For each model, this results in varying total volume and position for each cluster. Hence, the correlation can be evaluated cluster-wise, depending on the level of suppression or enhancement. First, for each cluster, the point-wise correlation was calculated.

Second, to overcome weaknesses of the general lower resolution of the BB MRI data to the CFD data, the averaged correlation between hemodynamic parameters and SI for each cluster was evaluated.

2.2.3 Particle tracking

To further elucidate the hemodynamics, 100,000 massless tracer particles were injected just proximal to the aneurysm. This provides a Lagrangian perspective of the flow and allows for a more direct calculation of the time fluid spends recirculating in the aneurysm as well as particular regions of interest such as regions experiencing high vorticity or extreme signal intensity. The particles provide not only residence time but also the evolving vorticity and rotation of the fluid as it transits the aneurysm.

3 Results

In this study, the flow pattern was quantitatively compared to the BB MRI signal intensity. Many of the coefficients appear to be statistically significant, showing a similar correlation in most of the models. First, the cluster-wise averaged values were compared. This results in a clear dependency of specific hemodynamic parameters for model 1 and 2. Correlation to signal intensity is high for kinetic energy and velocity magnitude. Vorticity magnitude shows a correlation to signal suppression. Vortex formation (Q-criterion) shows a

correlation to signal enhancement (correlation coefficient>0.77, p-value<0.05). The resulting parameters of model 3 differ depending on the inflow rate. For a high inflow rate, the enhancement and suppression show equal correlations as for model 1 and 2 (correlation coefficient>0.7, p-value<0.05). With a low inflow rate, signal suppression correlates with high vorticity (correlation coefficient >~ -0.7, p-value <0.05). Since model 3 appears to be a volumetrically small model, the low inflow rate does not affect sufficient signal intensities. Therefore, only the simulation with a high inflow rate shows reasonable results in the evaluation.

Table 2: Correlation coefficients and p-values for specific hemodynamic parameters compared to signal intensity for model 1 with low flow rate (150 ml/min)

Hemodynamic Parameter	Correlation coefficient	p-value
Kinetic energy	-0.82058	<0.05
Q-criterion	0.76965	<0.05
Vorticity magnitude	-0.78487	<0.05
Velocity magnitude	-0.93915	<0.05

Second, the point-wise correlation was considered to get a detailed insight into the quantitative dependencies. It reveals no significant correlations for any investigated hemodynamic parameter to the BB SI. Even when classified by equidistant clusters, no clear link was noticeable between the hemodynamic parameters and BB SI.

Concerning the particle tracers, certain elements show high vorticity inside the IA prior to washout. Few particles remain after four cardiac cycles. However, these high residence times indicate various flow behaviors and can span all clusters.

4 Summary

In this study, the comparison of hemodynamic parameters evaluated with CFD simulations to BB MRI SI is investigated. The correlation shows that kinetic energy and vortex formation can affect a signal suppression. Vorticity magnitude and velocity magnitude are related to signal enhancement. The point-wise correlation does not reveal deeper insight into the data. A further investigation of these hemodynamic parameters will take part in future studies as well as the increase of the number of analysed aneurysm models.

Future work will include the time-resolved CFD data of one heart cycle and not only compare the cycle-averaged

values (e.g., peak-systolic or diastolic time-points). SI can also be clustered not only by equidistant values but also spatially.

Author Statement

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