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Hemodynamics of anterior communicating artery aneurysms using combined imaging of the anterior circulation

Abstract: Intracranial aneurysms at the anterior communicating artery (AcomA) are associated with a higher rupture risk and a more challenging therapy since they are supplied with blood from both sides of the anterior vasculature. Since the standard imaging modality, i.e. digital subtraction angiography, involves the contrast agent injection into a single cerebral artery, this relationship cannot be satisfactorily considered in subsequent blood flow analysis based on the single-sided segmentation. In this study, we analysed five patients harbouring multiple intracranial aneurysms including those located at the AcomA. We virtually combined the segmentations from both sides into a single model and examined the influence on blood flow simulations based on different inlets: (1) only the left internal carotid artery, (2) only the right internal carotid artery and (3) both internal carotid arteries. Our results indicate a strong influence of the blood flow simulation for AcomA aneurysms as well as large differences between left and right side of the patient's vasculature.

Keywords: Anterior Communicating Artery, Blood Flow, Hemodynamic Simulation, Intracranial Aneurysms, Segmentation

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1 Introduction

Intracranial aneurysms (IAs) are complex diseases that arise from pathologic dilatations in the arteries of the brain. IA rupture and consecutive subarachnoid hemorrhage (SAH) are associated with high risk of morbidity and mortality. One site commonly affected by IAs is the Circle of Willis, a connecting circuit between the cerebral arteries at the base of the skull and brain. Aneurysms occurring at the anterior communicating artery (AcomA) are considered to be more complicated and critical compared to other IAs due to their location between the left and right anterior cerebral arteries (ACA) [1]. Thus, blood flow into the AcomA aneurysms may occur from either side, i.e. left or right ACA.

Unfortunately, 3D models acquired from digital angiography, the gold standard for clinical imaging of IAs, only cover a part of the patient's vasculature. Here, contrast agent is applied to a single artery, i.e. the left internal carotid artery (ICA), the right ICA or one of the vertebral arteries, yielding a data set containing the left, right or posterior part of the vasculature. In this study, we virtually combine these parts and analyse the influence on the hemodynamics of AcomA IAs.

2 Material and Methods

2.1 Material

Our study comprises five patient-specific data sets of patients suffering from multiple IAs with one located at the AcomA. Since the multiple aneurysms were manifested at the left and right side of the cerebral vasculature, 3D digital subtraction angiographic (DSA) data sets from both sides were acquired, see Figure 1.

All patients exhibited unruptured AcomA aneurysms except the fourth patient, who suffered from a ruptured AcomA IA.

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Figure 1: Combination of left and right vascular tree from a patient's left and right 3D DSA dataset. Both 3D models are combined into a single one.

2.2 Methods

2.2.1 Segmentation and Model Extraction

For each patient, a threshold-based segmentation of blood vessels was conducted in the contrast-enhanced 3D DSA image data with MeVisLab 2.8 (Fraunhofer MEVIS, Bremen, Germany, www.mevislab.de) for the left and right side. Next, the models were joined at the AcomA, based on close inspection of the original 3D DSA data.

2.2.2 Hemodynamic Simulation

For each patient, we used the three-dimensional vessel models to carry out highly-resolved simulations of the intra-aneurysmal blood flow. Hence, three simulations were conducted for each case, see Figure 2. The first one considers both ICAs as inflow cross-sections, the second one just the left and the third one just the right, respectively.

As pre-processing step, the surface models were converted into volume meshes via STAR CCM+ 2020.1 (Siemens Product Lifecycle Management Software Inc., Plato, TX, USA). For spatial discretization, a base size of $\Delta x = 0.5$ mm was chosen leading to approx. 0.5-1 million polyhedral and prism elements in total. The simulations were carried out using computational fluid dynamics (CFD). Specifically, the fluid dynamics solver STAR CCM+ was used, while a representative flow rate was scaled to the individual vessel cross sections [2]. For the outlet cross-sections constant pressure values were employed.

Further assumptions include the consideration of rigid vessel walls and approximation of blood as an incompressible ($\rho = 1055 \text{ kg/m}^3$), Newtonian ($\eta = 0.004 \text{ Pa} \cdot \text{s}$) fluid.

2.2.3 Hemodynamic Analysis

For a qualitative evaluation of the hemodynamic analysis, velocity-encoded streamlines were generated. For the subsequent quantification of hemodynamic parameters, we derived the individual wall shear stresses (WSS), mean velocity (V_m) and flow rate (Q) at characteristic locations of the 3D model [3]. In each case, the analysis was carried out for the entire vessel domain and the aneurysm, respectively.

Figure 2: For the virtually combined data sets, we conducted three hemodynamic simulations in each case: (1) both ICA inlets were activated (left), (2) only the left side was active (center) and (3) only the right side was opened (right). For the last two cases, the other ICA is treated as a wall.

3 Results

Based on the segmentations of the left side, the right side and the combination thereof, we obtained three flow fields for each patient. The CFD result was used to extract hemodynamic parameters, which are listed in Table 1-3.

Table 1: Quantitative results of the hemodynamic simulations for both activated inlets (DS = data set).

Parameter	DS 1	DS 2	DS 3	DS 4	DS 5
V_m at neck [$\frac{m}{s}$]	0.213	0.197	0.464	0.487	0.113
Q at neck [$\frac{ml}{s}$]	0.0115	0.0010	0.3570	0.0169	0.0015
V_m at left A1 [$\frac{m}{s}$]	0.409	0.59	0.71	0.93	0.42
V_m at right A1 [$\frac{m}{s}$]	0.0025	0.179	0.36	0.47	0.15
Q at left A1 [$\frac{ml}{s}$]	2.788	0.808	0.750	3.436	0.260
Q at right A1 [$\frac{ml}{s}$]	0.147	0.207	0.210	0.260	0.150
V_m for the whole aneurysm [$\frac{m}{s}$]	0.159	0.133	0.199	0.306	0.062
WSS for the whole aneurysm [Pa]	4.8	9.33	18.02	16.39	7.48

Table 2: Quantitative results of the simulations with only the left side as active inlet.

	DS 1	DS 2	DS 3	DS 4	DS 5
V_m at the neck [$\frac{m}{s}$]	0.255	0.198	0.562	0.661	0.232
Q at the neck [$\frac{ml}{s}$]	0.0042	0.0014	0.3730	0.0173	0.0202
V_m at the left A1 [$\frac{m}{s}$]	0.5475	0.623	0.939	1.072	0.465
Q at the left A1 [$\frac{ml}{s}$]	3.470	0.854	0.986	4.490	0.295
V_m for the whole aneurysm [$\frac{m}{s}$]	0.158	0.128	0.31	0.4	0.2
WSS for the whole aneurysm [Pa]	5.95	9.3	29.83	26.32	16.9

Table 3: Quantitative results of the simulations with only the right side as active inlet.

	DS 1	DS 2	DS 3	DS 4	DS 5
V_m at the neck [$\frac{m}{s}$]	0.106	0.0123	0.131	0.142	0.182
Q at the neck [$\frac{ml}{s}$]	0.0047	0.0004	0.103 1	0.8570	0.016 1
V_m at the right A1 [$\frac{m}{s}$]	0.233	0.324	0.46	0.6864	0.217
Q at the right A1 [$\frac{ml}{s}$]	1.330	0.376	0.857	3.840	0.190
V_m for the whole aneurysm [$\frac{m}{s}$]	0.032	0.0086	0.067	0.045	0.093
WSS for the whole aneurysm [Pa]	0.88	0.56	2.97	1.63	5.6

4 Discussion

When conducting our analysis, all simulated models with both ICAs as active inlets yield a higher velocity at the left side than on the right side. As a result, the WSS also increases proportionally at the points where the blood flow increases. For this reason, the simulated results (see example in Figure 3, row 3, left) show a higher WSS profile at the left side of the A1-ACA section compared to the opposite side.

Although no large differences between diameters of left and right A1 segments are noticeable in some data sets, it can be seen very clearly from Table 1 that the left A1 ACA in all models has a higher flow rate and mean blood velocity V_m than the right side. Among all models studied, the fourth data set with the ruptured AcomA aneurysm possesses the highest flow rates and V_m in the A1 segments. The mean velocity at the left A1-ACA exceeds the value of 0.9 m/s whereas on the right side is not greater than 0.5 m/s (see Table 1).

The relatively high blood flow in all examined patient data in the left A1 side can be attributed to patient-specific parameters. For this the abnormality of the Circle of Willis in the first data set is considered as a concrete example. In the first data set, the largest difference in blood flow is visible between the left and the right side of the A1-ACA, so that the flow through the left A1-ACA segment is more than one 90-fold higher than in the right A1-ACA (see Table 1). This can be interpreted by triplication of the A2 segments. The first two A2 segments are located on the left side and the third is located on the right side. For this reason, more blood flows through the left side to fill the abnormal artery in the left side of the brain.

The occurring unstable blood flow between the left and right side of the A1-ACA can lead not only to the formation of AcomA aneurysms, but also to further growth of the aneurysm and subsequent rupture, as demonstrated by the studies of Hassan et al [4] and Hernesniemi et al [5].

In addition, the ostia of the AcomA aneurysms in all reconstructed data sets have a direct contact with the left A1 segment, whereas the right side of the A1-ACA is connected at the bifurcation site to the A2 segment and the AcomA. This results in the left A1 segment having the greatest influence on the hemodynamics of the AcomAs. Whether the left side of the A1-ACA is frequently responsible for the high blood flow was not found in any other study.

Our study has several limitations. First, the findings of this study on AcomA aneurysms are based on a limited number of reconstructed clinical data, i.e. only five data sets. For this reason, further studies with a higher number of data set are necessary. Also, there is a lack of medical histories of the individual patients. Thus, other parameters, such as hypertension, smoking, family history of SAH and prior IAs, as well as chronic diseases, were not considered in this work since they were not available in the anonymized patient data from the clinic.

In addition, more detailed research should be conducted to determine how frequently the left A1 side had direct contact with the neck of the AcomA aneurysm and whether the left side of the CoW possesses the largest contribution to the overall hemodynamics.

5 Summary

The simulated data demonstrate an irregular blood flow through the two A1-ACA, which increases the mixing of blood within the AcomA aneurysms from the two supplying arteries. As a result, comparing the blood flow simulations based on left and right ICA as inlet yields large differences. Thus,

special care must be applied when acquiring the contrast agent-enhanced image data sets based on a single side. Preferably, for AcomA IAs which are supplied by both A1-ACAs, a combined model (i.e., a combination of left and right 3D DSA data) as presented in our study should be used for hemodynamic simulation and subsequent hemodynamic parameter analysis.

Furthermore, improved simulation settings could be applied for more realistic boundary conditions, e.g., an adjustable flow-splitting approach allowing for the variation of different treatment scenarios [6].

Author Statement

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Figure 3: The first row illustrates three representations of the WSS from three different angles, such that on the first image on the left the two A1-ACAs and on the other two the AcomA aneurysms can be seen. Subsequently, the same angles are used in the second row where the blood flow and the occurring velocity distribution are visualized via streamlines. In the third and fourth row, the WSS and the streamline views are generated based on the left ICA as active inlet (left), the right ICA as active inlet (right) or both ICAs as active inlets (center).