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COMPARISON OF CEREBRAL ANEURYSM FLOW FIELDS OBTAINED FROM CFD AND DSA

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INTRODUCTION

Quantifying the flow dynamics in cerebral aneurysms is important to understand the mechanisms responsible for aneurysm progression and rupture and develop improved aneurysm risk assessment procedures (diagnosis) as well as for understanding and evaluating endovascular interventions such as flow diversion (treatment).

Many studies have used computational fluid dynamics (CFD) to model the flow in cerebral aneurysms to study rupture as well as flow diversion treatments. On the other hand, attempts at measuring the *in vivo* flow fields have been made with phase-contrast magnetic resonance as well as dynamic angiographic velocimetry [1]. The latter technique is attractive because it can be carried out during the angiographic evaluation of the aneurysm or during its endovascular treatment.

Previous studies have shown the potential clinical value of the angiography-based flow quantification and have compared the results to Doppler ultrasound and synthetic angiograms generated from CFD simulations [2, 3]. The purpose of our study was to further evaluate the angiography-based flow field quantification by comparing against patient-specific CFD models with angiographic aneurysm patient data.

METHODS

A total of 15 cerebral aneurysms imaged with 3D rotational angiography (3DRA) and 2D digital subtraction angiography (DSA) at 60 frames per second were studied. The DSA images were acquired from two different viewpoints trying to minimize the overlap between the aneurysm and the surrounding vessels. In two patients only a single view was acquired (total 28 views for all 15 patients).

Two dimensional flow fields in the aneurysm and connected vessels were reconstructed from the corresponding DSA images using a previously developed optical flow technique [1]. The mean aneurysm flow amplitude (MAFA) was calculated from the DSA images in the aneurysm region as in previous studies [4].

Patient-specific CFD models were constructed from the 3DRA images and ran with pulsatile flow conditions derived from DSA-based flow measurements in the parent artery. The mean aneurysm flow velocity (VEL) was computed as the spatial average of the CFD velocity magnitude over the aneurysm region and over time.

Since the DSA and 3DRA images were acquired relative to the same reference frame, the CFD flow fields were projected to the same views used in the DSA acquisitions. Both the DSA and CFD flow fields were averaged over the cardiac cycle, and the CFD flow fields were further averaged along the line of sight. The DSA and CFD flow fields were then compared visually by plotting streamlines in the projected 2D images, and quantitatively using a similarity measure defined as:

$$s = \frac{1}{N} \sum_{i \in ROI} \boldsymbol{a}_i \cdot \boldsymbol{b}_i / (|\boldsymbol{a}_i||\boldsymbol{b}_i|) \quad (1)$$

where $\boldsymbol{a}_i$ and $\boldsymbol{b}_i$ are velocity vectors in the two flow fields, ROI the region of interest, N the number of pixels in ROI, and the $\cdot$ operator denotes the dot product. This quantity measures the similarity of the directions of the two vector fields. A similarity of 1 means a perfect match, random input would yield 0, and opposing fields would give -1.

RESULTS

The average similarity of all DSA and CFD flow fields was s=0.66. Restricting the comparison to the vessel (i.e. excluding the aneurysm region) resulted in an average similarity of s=0.78. Considering only the aneurysm regions, the average similarity was s=0.37.

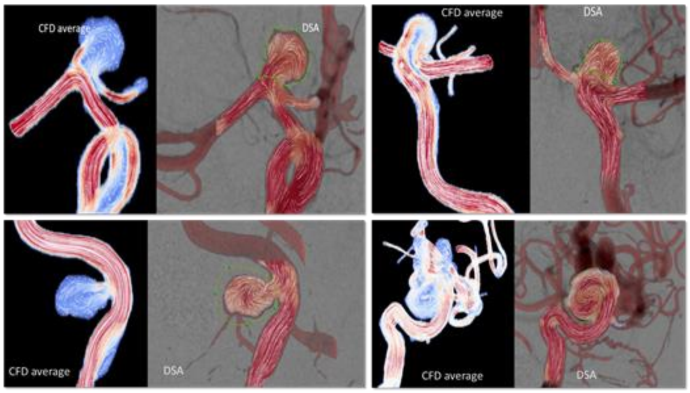

Fig. 1: Average CFD and DSA flow fields in good agreement.

In 8/15 patients (53%) there was at least one view in which the CFD and DSA flow fields agreed with a similarity s>0.5. Four examples are shown in Fig. 1. In these cases, the main intra-aneurysmal vortex structures are seen in both fields.

An important issue affecting the results of the DSA flow quantification is overlap between the aneurysm and surrounding vessels. Two examples are shown in Fig.2. In the first case (top), the overlap is emphasized by computing the maximum intensity projection (MIP) along the line of sight (left most picture), and can be seen to affect both the projected CFD and the DSA flow fields. In the second case (bottom), the aneurysm wraps around the parent vessel making it impossible to find a view without vessel overlap. Nevertheless, the main vortex structure inside this aneurysm is well captured by the DSA flow.

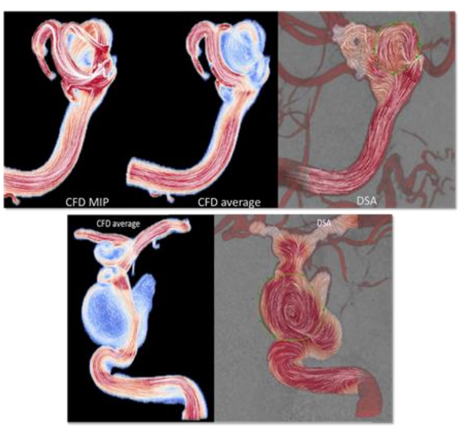

Fig. 2: CFD and DSA flow fields in cases with overlapping vessels.

In 7/15 patients (47%) the DSA and CFD flows did not agree (s<0.5). Some of these disagreements were due to vessel overlaps as explained before, but in other cases a “sink” effect was observed in the DSA field where the flow is directed towards the center of the vortex instead of around it. Two examples of are presented in Fig.3. In the first case (top), it can be seen that within the aneurysm the DSA flow points radially towards the center of the vortex seen in the CFD flow. In the second case (bottom), the DSA flow seems to go over the vortex center seen in the CFD field. This effect could be due to under sampling in the DSA quantification. This may happen when the time interval between DSA images is comparable to the time it takes for a particle to travel around the vortex core. For example a particle that is initially seen at the aneurysm inflow would be seen in the next frame close to the exit, and thus the trajectory would look like those of the bottom case of Fig. 3. It may also occur when the cardiac wave length is large compared to the aneurysm perimeter.

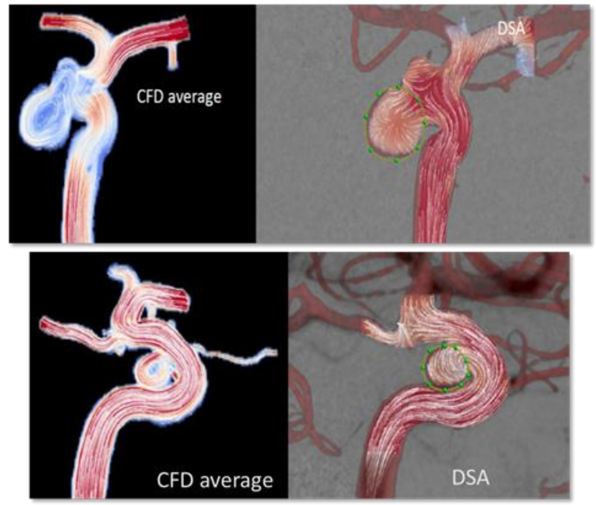

Fig. 3: Cases where a “sink” effect can be seen in the DSA flow.

The mean aneurysm velocity (VEL) and MAFA values are compared in Fig. 4 (left). After discarding views with significant vessel overlaps (red dots) regression analysis shows a linear correlation between VEL and MAFA (R=0.80, p<0.0001). However, the relative difference between VEL and MAFA increases with VEL (fig. 4, right) which is consistent with the notion of under sampling for a fixed frame rate when the aneurysm velocity increases.

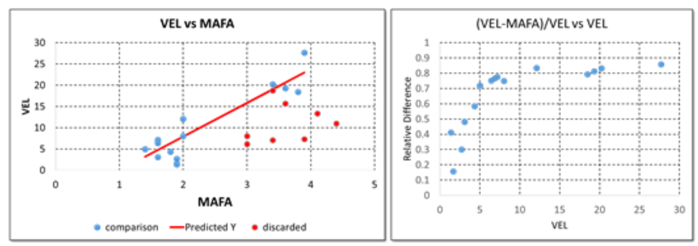

Fig. 4: Relation between MAFA and mean aneurysm velocity (left), and relative difference (right).

DISCUSSION

In general there was good agreement between DSA and CFD flow fields. In the aneurysm, where the flow can be quite complex the agreement was not as good as in the vessel. In some cases a “sink” effect was observed that could be due to under sampling. Further study is necessary to understand this effect. Vessel overlap has a strong influence on DSA flow results and should be avoided, however sometimes it is not possible to find views without overlapping vessels.

The MAFA value previously defined seems to be linearly correlated with the mean aneurysm velocity, which suggests that it could be a good parameter to evaluate aneurysms or treatments. However, the difference between the MAFA and the mean aneurysm velocity increases with the velocity. Increasing the framerate of the DSA measurements could improve both the agreement of the MAFA with the mean aneurysm velocity and resolve the “sink” effect.

ACKNOLEDGEMENTS

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