CE-MRA and PC-MRI in the Evaluation of Hemodynamics in Intracranial Aneurysms

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Abstract
We describe here the use of *in vivo* and *in vitro* PC-MRI to predict and validate computational fluid dynamics modeling (CFD) simulations of hemodynamics in patients with intracranial aneurysms. In addition to validating computational results in existing conditions, PC-MRI phantom studies were used to validate CFD simulations of the effects of different potential interventions. The results highlight the power of MRI as a quantitative measurement and imaging tool for intracranial vascular anomalies.

Introduction
Giant fusiform aneurysm treatment is particularly challenging, and options such as occluding the basilar artery, inserting a stent through the aneurysm, or surgically reducing the aneurysm by clipping, are all drastic measures that have a low probability of success and are only resorted to when the risk posed by the aneurysm is considered to be very profound. It has recently been demonstrated that advanced CFD methods have the ability to predict velocity fields and other hemodynamic parameters, on a patient-specific basis [1-3]. CFD methods are also able to simulate conditions that do not currently exist, and can therefore be used to predict the hemodynamic consequences of a surgical intervention. Widespread acceptance of CFD methods in the clinical environment requires *in vivo* and *in vitro* validation studies. Although PC-MRI has been used to validate CFD in generalized geometries [4], it must be able to validate CFD for patient-specific geometries to increase confidence in its use.

Results and Discussion
Thirteen patients with intracranial aneurysms were enrolled using IRB consent. Patients with fusiform aneurysms were imaged with CE-MRA and PC-MRI to determine lumenal geometry and flow waveforms in the inlet and outlet vessels, respectively. The 3D CE-MRA data was surface rendered for CFD. Calculations were performed using the same velocity waveforms and magnitudes as were measured *in vivo.* Comparisons of CFD predictions and velocity fields measured in the plane of the aneurysm were compared. Excellent agreement was found between the velocity fields predicted using CFD and those from in plane *in vivo* PC-MRI. Below we show the results of predictions for different interventional options in a patient with a giant fusiform basilar aneurysm. CFD modeling was performed for three flow scenarios: A) Flow conditions, including the patient stenosis, equal to those measured in the patient, i.e., ten times more flow through the right vertebral artery than through the left; B) Equal flow through both vertebrals that would result from opening the vertebral stenosis by stenting; and C) Flow conditions resulting from opening the vertebral stenosis and occluding the contralateral vertebral artery. Wall shear stress was also calculated for the three flow scenarios.
A silicone phantom containing an exact replica of the aneurysm geometry was connected to a flow loop and imaged with PC-MRI. The three flow scenarios described above were modeled by clamping either of the two input tubes into the model. The results from the *in vitro* flow data showed that the CFD had accurately predicted the flow outcomes (Figure 1).

Conclusion
This study demonstrates that patient-specific CFD is in excellent agreement with PC-MRI measurements. Further, it demonstrates that exact phantom replicas can be used to predict patient-specific hemodynamic factors after different interventional treatments and can validate CFD predictions. PC-MRI can be used *in vivo* to acquire baseline flow conditions and also *in vitro* to map the resulting flows. On the basis of the *in vitro* results, we can describe the effects that different interventional procedures would have on the flow patterns and wall shear stress within the aneurysm, showing that opening a currently stenosed vertebral artery and occluding the other would result in a shifting and reduction of the low wall shear stress in the growth zone of the aneurysm.

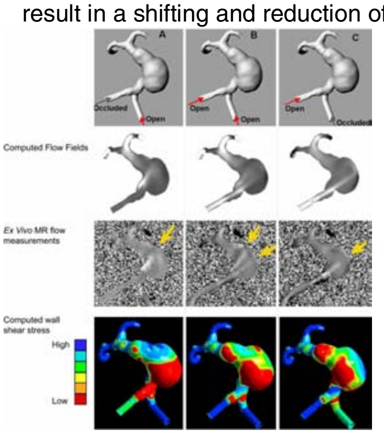

Figure 1: The resultant flow fields and wall shear stress for the three flow scenarios

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