NEUROSURGICAL FOCUS



ONLINE ONLY

# Supplemental material

**Hemodynamic and morphological characteristics of a growing cerebral aneurysm**

Dabagh et al.

https://thejns.org/doi/abs/10.3171/2019.4.FOCUS19195

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**Appendix A. PATIENT AND METHODS**

The following are the information about the CTA images: slice size was 512 x 512 in all three stages; slice thickness (mm) was 0.625, 1.6, and 1.6 in three stages; pixel size (mm) was 0.232369, 0.390625, and 0.390625 for three stages, respectively.

The CTA datasets corresponding to the three stages were segmented and the computational meshes representing the 3D topology were created using Mimics software (Materialise, Leuven, Belgium). To quantify morphological changes between two proceeding stages of CA growth, a part-comparison analysis was conducted using Materialise 3-matic software (Materialise, Leuven, Belgium). The analysis computes the local Hausdorff distance showing the local morphological differences between the two 3D. The three-dimensional (3D) models corresponding to two consecutive stages of CA growth (early and mid-stages as well as mid and late stages) were overlaid using global registration to exclude differences due to different patient positioning. Then, the part comparison was performed between (a) early and mid stages, and (b) mid and late stages.

Five geometric features of the aneurysm at each stage of growth were also calculated: (1) aneurysm height (H), (2) aneurysm width ($W_A$), (3) neck width ($W_N$), (4) aspect ratio ($H/W_A$), and (5) ratio of neck width to parent vessel width at inlet ($W_N/ W_P$). The results are reported in Supplementary data.

**Appendix B. Data analysis** ParaView-5.2.0 (Kitware Inc., 2007) was used for post-processing analysis to quantify root-mean-squared velocity magnitude ($V_{rms}$) as well as visualizing aneurysmal hemodynamic quantities including WSS, TAWSS, vorticity, OSI, and flow pattern. In-house MATLAB codes (Matlab R2017a, The MathWorks Inc., Natick, MA) were used to calculate the distributions and percentage bin (within a histogram bin) of WSS, TAWSS, vorticity, and OSI for all three aneurysm models.

In-house MATLAB codes were applied to determine the statistical significance of the correlations (via sensitivity analysis) between hemodynamic factors and the morphological changes (growth rates) among the two consecutive growth stages.

**Appendix C. Particle image velocimetry (PIV)**

All three patient-specific growing CA models were translated to lost-core, optically clear urethane models for PIV experimentation. The physical model was placed on a translation stage and connected to a flow loop consisting of a (1) reservoir, (2) peristaltic pump, (3) compliance chamber, (4) resistance valve, and (5) digital flowmeter. The compliance chamber was used to dampen the pulsatile flow waveforms produced by the peristaltic pump. The resistance valve was connected in parallel to the main part of the flow loop and was used to modify the amount of flow entering the model. In order to ensure that the desired flow rates were explored, the flowmeter was connected downstream to the physical model. The reservoir was filled with sodium iodide-glycerin-water mixture and seeded with 8 μm fluorescent particles. FlowMaster 3D Stero-PIV (LaVision, Ypsilanti, MI, USA) system was used to capture the particle images. A dual-pulsed Nd:YAG laser was used as the light source, and two CCD cameras placed in stereoscopic configuration was used to capture the particle images.

The beam of light from the laser was formed into a light sheet using an optical arrangement of cylindrical and spherical lenses housed within the laser unit. Particle images were acquired at five parallel planes, separated by a distance of 0.5 mm, within the aneurysm volume. Steady inflow rate of 3 mL/s was prescribed at the model inlet, and 100 image pairs containing the particles (at each plane) were acquired. The velocity vectors were calculated using an in-build cross-correlation algorithm within the DaVis software (LaVision, Ypsilanti, MI, USA). Initial and final interrogation window sizes of 32 x 32 pixels and 16 x 16 pixels, respectively were used. The velocity vector distribution along the center-plane of the aneurysm, color-coded by $V_{rms}$ , in the X, Y and Z direction from the PIV results are compared to the values obtained from HARVEY to serve as validation of the HARVEY simulations, in this regime.

**Appendix D. Visualization of vertical flow in cerebral aneurysm and detection of the vortex center**

The flow pattern within aneurysm volume was investigated qualitatively using basic technique such as selectively seeded streamline and glyphs in ParaView-5.2.0 (Kitware Inc., 2007). The streamlines were seeded at the entrance of the aneurysm in all models. Seeding density and path length of the streamlines were manually set. Then, several slices were selected in recirculation area with 0.05 mm distance. The coordinates and velocity data of the slices, within aneurysm sac volume, were extracted.  A quantitative investigation to detect the vortex center was performed using in-house MATLAB code (Matlab R2017a, The MathWorks Inc., Natick, MA). Contours were drawn at each slice which led to detect the center of vortex accurately.