VESEEL WALL ENHANCEMENT IS ASSOCIATED WITH INCREASED WALL STRESS IN INTRACRANIAL ANEURYSMS

Sricharan S. Veeturi (1,2), S. Mostafa Mousavi J. S (1,2), Ammad A. Baig (2,3), Andre Monteiro (2,3), Adnan H. Siddiqui (2,3), Vincent M. Tutino (1,2,3,4,5)

(1) Department of Mechanical and Aerospace Engineering, University at Buffalo, Buffalo, NY, USA
(2) Canon stroke and vascular research center, Buffalo, NY, USA
(3) Department of Neurosurgery, University at Buffalo, Buffalo, NY, USA
(4) Department of Biomedical Engineering, University at Buffalo, Buffalo, NY, USA
(5) Department of Pathology and Anatomical Sciences, University at Buffalo, Buffalo, NY, USA

INTRODUCTION

Vessel wall enhancement has emerged as a potential imaging biomarker for risk stratification of intracranial aneurysms (IAs). This is a phenomenon wherein the presentation of the aneurysm wall on contrast-enhanced MRI (CE-MRI) exhibits markedly higher signal intensity as compared to its presentation on the baseline or non-enhanced MRI (NE-MRI). Vessel wall enhancement (VWE) of the aneurysm wall has been correlated with inflammation in the IA, as well as growth and rupture [1]. However, the underlying tissue mechanobiology in regions of high VWE, which could be related to rupture, remain poorly understood.

Stress in the aneurysm wall tissue could be related to the VWE phenomenon, as aneurysm growth and remodeling are thought to be driven, in part, by vascular smooth muscle responses to abnormal arterial stresses [2]. To measure mechanical stress in the IA wall, finite element analysis (FEA) is a particularly useful tool. Previous studies have shown that IAs exhibiting VWE had a significantly higher 95th percentile wall tension as compared to IAs that did not, showing a potential correlation between mechanical forces in the aneurysm wall and VWE [3]. However, their model used generic assumptions about the internal pressure as well as the IA wall thickness. Variations in thickness and pressure could influence stress distributions in the IA.

In this preliminary study, we investigate the effect of using patient specific internal pressure as well as patient specific wall thickness on the potential correlation between VWE and the Von-mises stress in the aneurysm wall.

METHODS

In the current study, approved by the IRB (Study 00004370), we collected patient specific 3D Time of flight TOF-MRA image as well as T1 weighted NE-MRI and CE-MRI. The MRA image was used to segment and generate 3D stereolithographic (STL) geometry file for the aneurysm. We then used OpenFOAM V6 to perform hemodynamics as described in previous studies [3]. Assuming the time-averaged inlet pressure to be 90 mm Hg, we generated pressure maps on the IA wall, which were used as loads in FEM simulations.

We then used the NE- and CE-MRI to manually reconstruct the aneurysm wall. This was then used as a point cloud in an in-house MATLAB code (R2021) to generate thickness for each triangulated surface on the STL file. The reconstructed volume of the aneurysm wall was used as input for the FEA simulation. We assumed a location based uniform thickness of 0.58 mm for the parent artery [5].

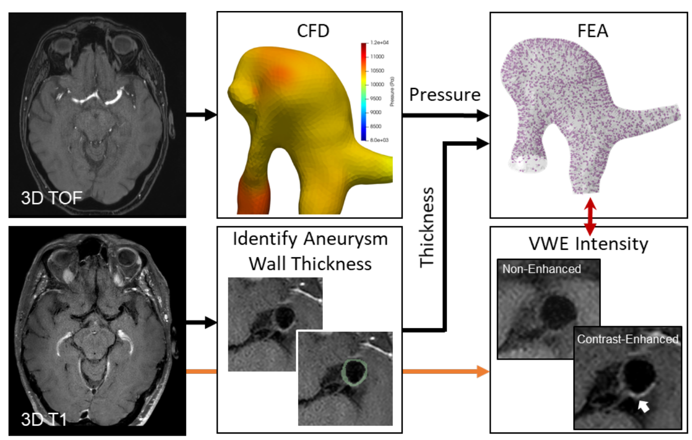

Figure 1: Modeling Workflow. From 3D TOF images we reconstruct aneurysm geometry, find blood flow characteristics using CFD, and implement variable pressure on the geometry. From 3D T1 imaging, we find aneurysm thickness and map it on aneurysm geometry. Also, from latter imaging modality we find VWE and compare it to FEA results.

We used Abaqus CAE/2019 to perform FEA models on the aneurysm in four different models: (1) uniform thickness and uniform pressure of 90 mm Hg (UTUP) (2) patient-specific thickness and uniform pressure (PTUP) (3) uniform thickness and patient-specific pressure (UTPP) (4) patient-specific thickness and patient-specific pressure (PTPP). Aneurysm wall was modeled as shell elements. Material models follow a nonlinear hyperelastic model describe previously [6]. For the variable pressure cases, average pressure of one cardiac cycle at different coordinates of aneurysm wall was withdrawn from CFD analysis and implemented on the inside of aneurysm wall. For the uniform pressure, we used the values from a previous study [7]. To map the variable thickness, nodal distribution was used.

Finally, we used previously established method to map the MRI signal intensity in CE-MRI onto the aneurysm wall [8]. We used the intensity at the genu of corpus callosum for normalization of MRI signal intensity (CC_{ratio}). Enhancing regions in the sac were defined as areas with $CC_{ratio}>1$. We performed univariate analysis to investigate the differences in Von-Mises stress in enhancing and non-enhancing regions in all the 4 FEA models after isolating the aneurysm sac manually. Furthermore, we also evaluated the potential correlation between CC_{ratio} and Von-mises stress in all the models.

RESULTS

The aneurysm sac was 8.3 mm in size and was located at the middle cerebral artery. The thickness map generated is shown in figure 3A. We observed that enhancing regions had a significantly higher wall thickness as compared to non-enhancing regions ($p<0.001$) which is also shown in previous literature.

In our FEA analysis, we found that enhancing regions had significantly higher Von-Mises stress as compared to non-enhancing regions ($p<0.001$) in all the models. Qualitatively, we observe that the type of pressure loading used has negligible effect on the stress contours ($R^2>0.99$) in both fixed thickness as well as variable thickness models. However, using aneurysm specific thickness values does indeed have an effect on the stress distributions ($R^2=0.54$) as shown in figure 2.

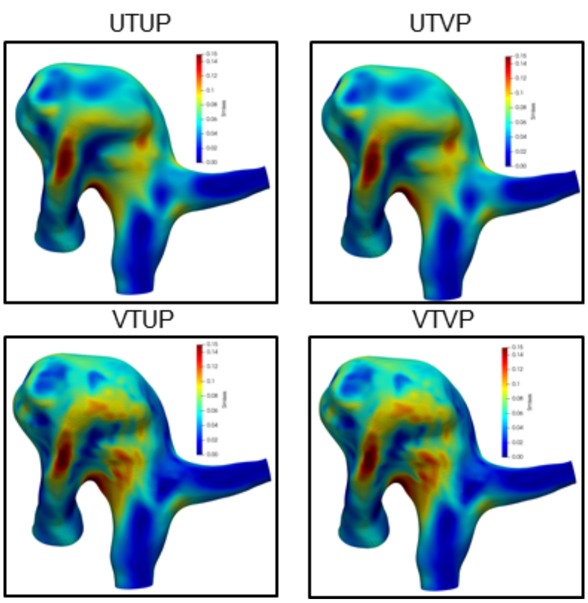

Figure 2: Contours of Von-Mises stress distribution across different models. We observed no noticeable change in the stress values when varying pressure was used across the aneurysm as compared to generic uniform pressure loading. However, we do find changes in stress values when varying values of wall thickness are used.

We also found that enhancing regions had significantly higher stress values than non-enhancing regions as was found by previous studies [3]. However, we found that there was only a weak linear correlation between CC_{ratio} values and Von-mises stress in all the models. The correlation of intensity and stress values for different models was as follows: UTUP: 0.094, UTPP: 0.096, PTUP: 0.139 and PTPP: 0.14.

DISCUSSION

In this study we developed a pipeline for investigation of the potential relationship between aneurysm wall stress and the vessel wall enhancement phenomenon. We found that enhancing regions in the aneurysm had a significantly higher stress than non-enhancing regions. VWE is an indication of inflammatory cell infiltration and neovascularization which have been associated with aneurysm instability and rupture. Hence, it is possible that the regions that have high stress and exhibit enhancement could indicate a damaged wall which is under high stress. Eventually, these regions may degrade further and cause an imbalance in forces which could lead to rupture of the aneurysm. Additionally, we also observed that thickness of the aneurysm has an effect on the stress distributions and using varying pressure does not. Thus, using patient specific aneurysm thickness is advised when possible.

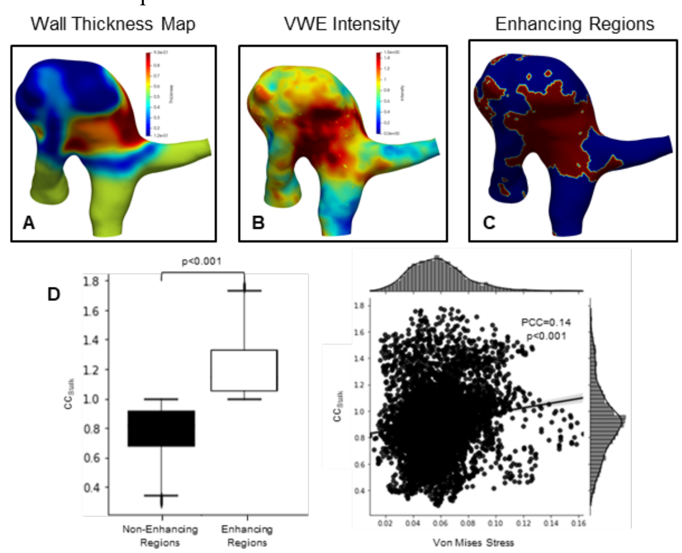

Figure 3: Contours of wall thickness, VWE mapped intensity and enhancing regions. A). Heat map of wall thickness. We observed higher thickness in enhancing regions. **B).** Heat maps of mapped vessel wall intensity (CC_{ratio}) across the aneurysm. **C).** Visualization of enhancing and non-enhancing regions in the aneurysm. **D).** Univariate analysis and correlation plots of stress values in enhancing and non-enhancing regions.

REFERENCES

[1] Edjlali, M et al., *Neuroradiology*, 289:181-187, 2018.
[2] Frosen, J et al., *Stroke*, 35:2287-2293, 2004
[3] Galloy, A et al., *Frontiers in Neurology*, 12, 2021
[4] Veeturi, SS et al., *Royal society Open Science*, 8, 2021
[5] Hartevald, A et al., *Data in Brief*, 19: 6-12, 2018
[6] Shang, EK et al., *Circulation,* 128: S157-S162, 2013
[7] Steinman, DA et al., *Journal of Biomechanical Engineering*, 135, 2013
[8] Veeturi, SS et al., *Diagnostics*, 11: 1742, 2021