Designed to Burst: Simulating Cerebral Aneurysm Rupture Using 3D Printing

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Abstract

- Cerebral aneurysms form from a weakened arterial wall. [1]
- Rupture causes half a million deaths annually worldwide. [2]
- **Purpose**: Understand the behavior and effects of aneurysm rupture on brain tissue.
- **Goal**: Develop a functional, rupturing phantom model that accurately mimics the biomechanical properties of a cerebral aneurysm.
- **Method:** Uses a computational model to locate weak spots and adjust wall thickness at these locations to mimic wall-thinning phenomena.
- **Expectations**: Easy-to-fabricate and cost-effective working model with predictable rupture with respect to location

Methods

Geometry Identification

- Three patient-specific models (Figure 1)
- Simulated in SimVascular
- Overlapping regions of low WSS and high OSI identified in ParaView
- Models weakened to wall thicknesses of 0.15 mm, 0.20 mm and 0.25 mm (Figure 2)

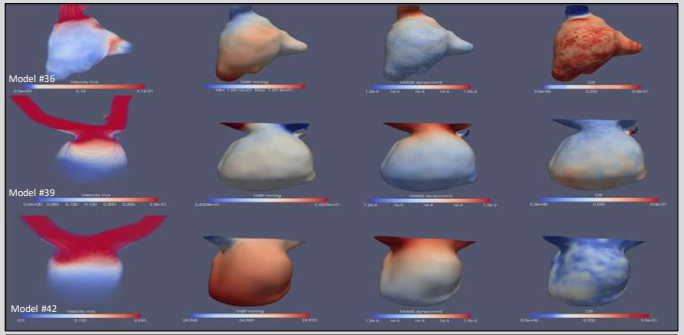

Figure 1. Results from SimVascular Simulation. Showing Velocity, Time Averaged Blood Pressure, Time Averaged Wall Shear Stress, and Oscillatory Shear Index. Simulation was conducted with a Max Flow Rate of 1.8 cc/s and RCR outlet BC. [3]

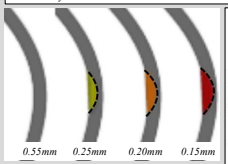

Figure 2. Simplified Weakened Aneurysm Wall Thickness Schematic. Gray area represents aneurysm wall; colored area and dashed lines represent wall thinning.

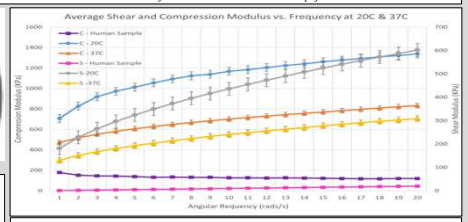

Figure 3. Elastico Clear Young's Modulus Material Test Results.

Aneurysm Material Selection

- Rheometer tests: oscillating shear force, constant compression force, constant tension force, and ultimate tensile comparing Elastico Clear to human specimens in Figure 3. [4]

Brain Matter Material Selection

- Brain mimic material: 4% Wt concentration of bovine skin gelatin.
- Transparent, E = 2.06 - 29.7 kPa, ρ = 1.2 g/ml, Poisson's ratio = 0.451
- Brain tissue properties: E =1 kPa, ρ = 1.04 g/ml, Poisson's ratio = 0.48

Setup

Phantom Design and System Integration:

- 3D printed aneurysm held by aneurysm holder and connected to specific inlet and outlet tubes
- Blood mimic (54.1% glycerin) is pumped through system, with the agarose gel molded around the aneurysm.
- Blood mimic maintained at 37°C via circulating water bath

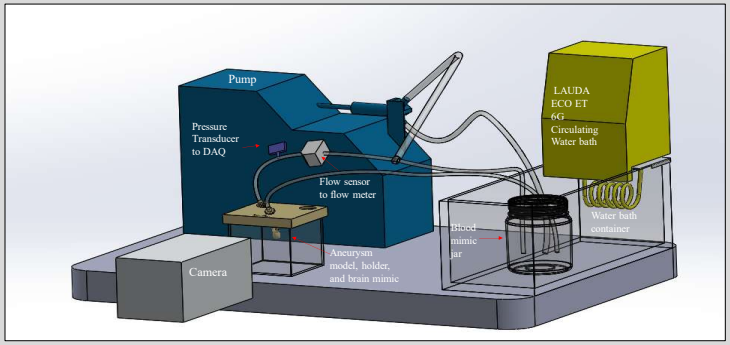

Figure 4. System Setup CAD, Depicting Testing Setup. The Pulsatile Pump (Left) Delivers Flow Into The System at 60 Pulses Per Minute.

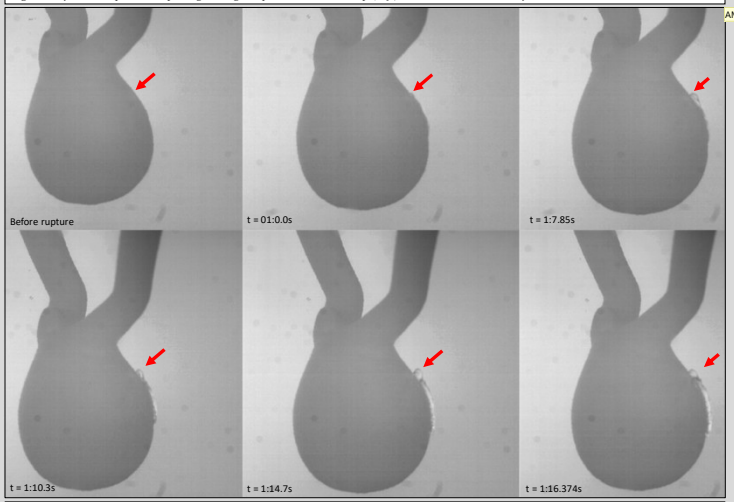

Figure 5. The sequence of images, progressing from the top left to the bottom right, illustrates the development of flow from the phantom model. These images were captured using a NanoSense MkII at a rate of 1000 Hz, recording a total of 16374 frames over 16.374 seconds.

Testing Procedure:

1. Close off valves to the aneurysm (open to the rest of the system).
2. Set flow rate: 100 ml/min, pressure: 120/60 mmHg.
3. Turn off the pump and open the valves to the aneurysm model
4. Turn on DAQ/LabVIEW/Camera and start the pump.
5. Record the time until rupture and observe behavior.
6. If no rupture occurs within 10 minutes of starting the system, raise the pressure in 20 mmHg increments. Repeat process 4-5 three times.

Results

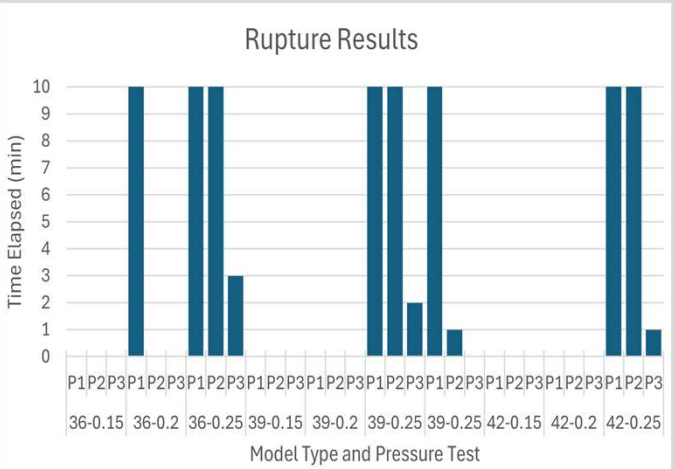

Figure 6. Results of Rupture Time: Observed Elapsed Time Until Rupture for Each Pressure Condition and Wall Thickness. Model type indicated by # - wall thickness. P# denotes Stage of Hypertension, with P1 being Normal (120/80 mmHg), P2 being Stage 2 (159/99 mmHg), and P3 being a Crisis (>160/>100 mmHg)

According to Figure 6, every model ruptured under the third test, which mimicked a hypertensive crisis. Patient model 39 demonstrated the most realistic and predictable rupture results, aligning closely with predictions.

Conclusion

- Successfully developed patient-specific 3D printed cerebral aneurysm phantom models
- Weak points identified using computational fluid dynamics (CFD) and implemented into models with varying wall thicknesses.
- The model was attached to a closed-loop circulatory system with blood mimic fluid to simulate human body conditions.
- Experimental trial results: wall thickness influences pressure threshold before observed rupture.
- Supports the application of this model type in the use of medical device testing, surgical training, and diagnosis criteria.

References

[1] Mayo Clinic, "Brain aneurysm - Symptoms and causes," *Mayo Clinic*, Mar. 07, 2023.
[2] "Statistics and Facts" Brain Aneurysm Foundation.
[3] Updegrove, A., Wilson, N., Merkow, J., Lan, H., Marsden, A. L. and Shadden, S. C., SimVascular - An open source pipeline for cardiovascular simulation, Annals of Biomedical Engineering (2017) 45: 525. DOI:10.1007/s10439-016-1762-8 (2017)
[4] Norris et al., *J. of bio. materials research*, 110(3), 612-622.

Acknowledgements

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Slide 1

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