Computed Tomography Circulation Phantom to Assess Hyperdynamic Contrast Flow Rates

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Motivation and Problem Statement

- Since COVID-19, cases of cardiopulmonary failure requiring Veno-Arterial Membrane Oxygenation (VA-ECMO) have risen [1]
- Patients on VA-ECMO may require a (CT) scan [2]
- Limit exposure to radioactive iodinated contrast dye [3]
- Currently, there is no medical standard involving contrast injection for patients on VA-ECMO
  - Oxygenated blood is pumped retrograde to typical blood flow

Goal: Create a phantom for research and development of best practices for VA-ECMO imaging.

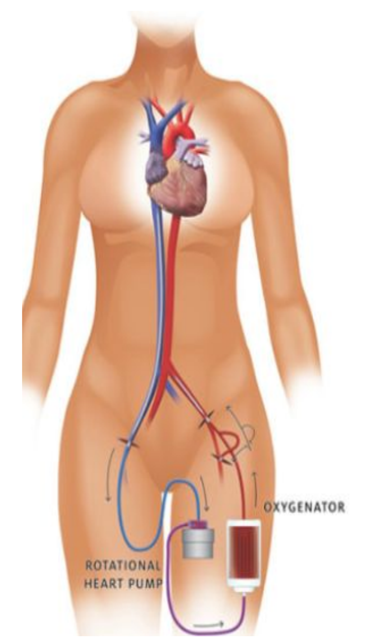

Figure 1: Diagram of an individual on ECMO.

Fundamental Equations and Definitions

Hagen-Poiseuille Equation[4]:

$$\Delta P = \frac{\pi r^4 Q}{8 \eta L}$$

Describes the variables that contribute to pressure difference (a critical variable) in the system

Reynolds Number[5]:

$$Re = \frac{\rho V L}{\eta}$$

A quantity that classifies the flow into turbulent or laminar and determines mixing capabilities

Hounsfield Unit (HU): A relative quantitative measurement for CT images indicative of the attenuation coefficient of radiation within materials [6]

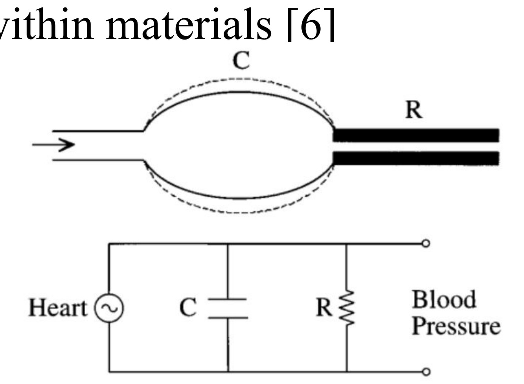

Figure 2: Windkessel Model of the Cardiovascular system. Top schematic showing fluid mechanical elements for arterial capacitance and resistance of the elastic aorta. The bottom schematic showing corresponding electrical elements used for this model [7].

Design Criteria

- Circuit models anatomical aortic arch location with at least 60cm between pump and aorta [8]
- Time for contrast dye to reach steady state on CT scan is within 10 seconds of patient data
- Adjustable flow rates up to 6L/min to mimic human physiological blood flow and ECMO output [9]
- 6 L reservoir of fluid
- Iodinated contrast injector access point
- Eliminate leakage within circuit and limit build up of bubbles
- Entire phantom should be set up and moved with ease

Methods and Final Design

Steps for Fabrication:

1. Export model from patient CT scan
2. Use 3D modeling software to add connectors
3. 3D print model and perform post processing
4. Connect model to full circuit

Figure 3: Virtual 3D model of phantom in Blender, prior to processing.

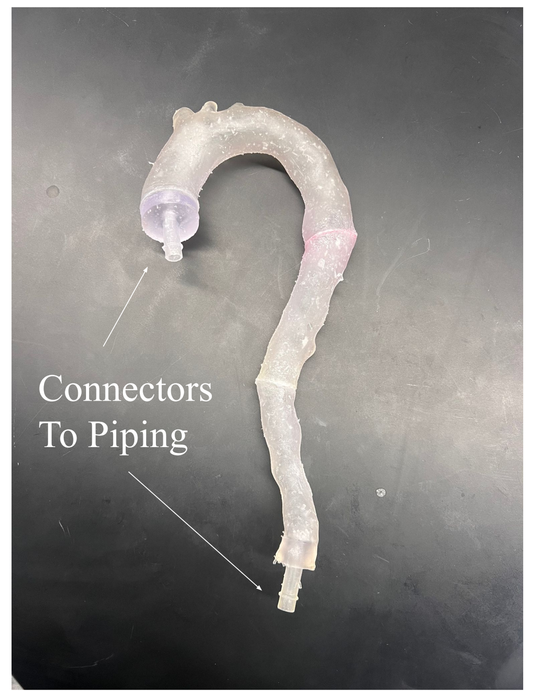

Figure 4: Elastic 50A Resin 3D printed Aorta phantom.

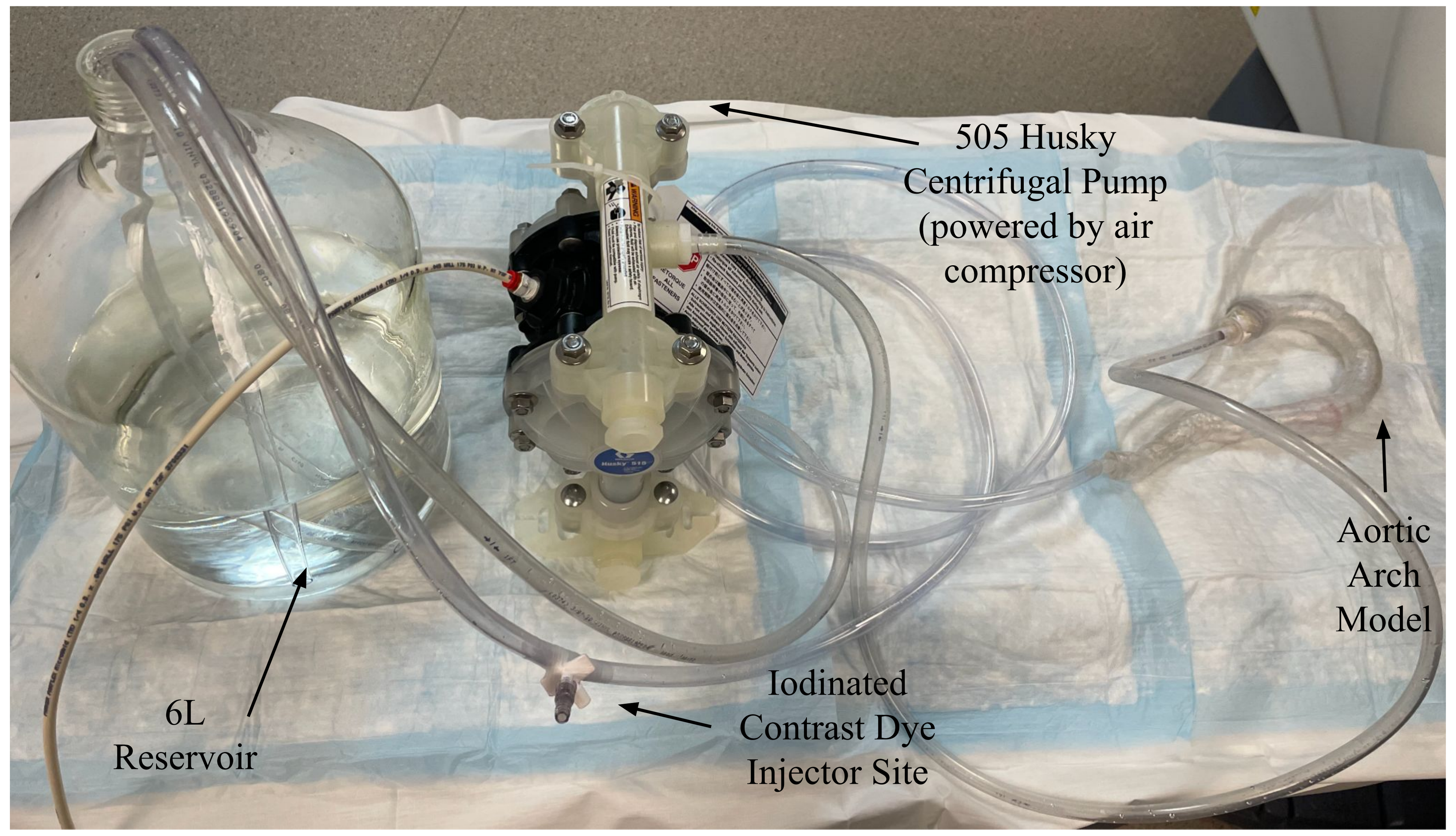

Figure 5: Complete phantom with pump, tubing, and aortic arch model.

Testing and Results

- **Flow Rate Calibration**: Linear regression model that converts pressure of air compressor to volumetric flow rate of pump output
- **Leakage**: Temporal weight measurement to determine amount of water loss during 150 seconds of operation
- **CT scan**: Perform scan with contrast injection to determine the time to reach Hounsfield Unit ROI steady state and compare to patient case

Figure 6: Circuit on the CT table prior to scanning.

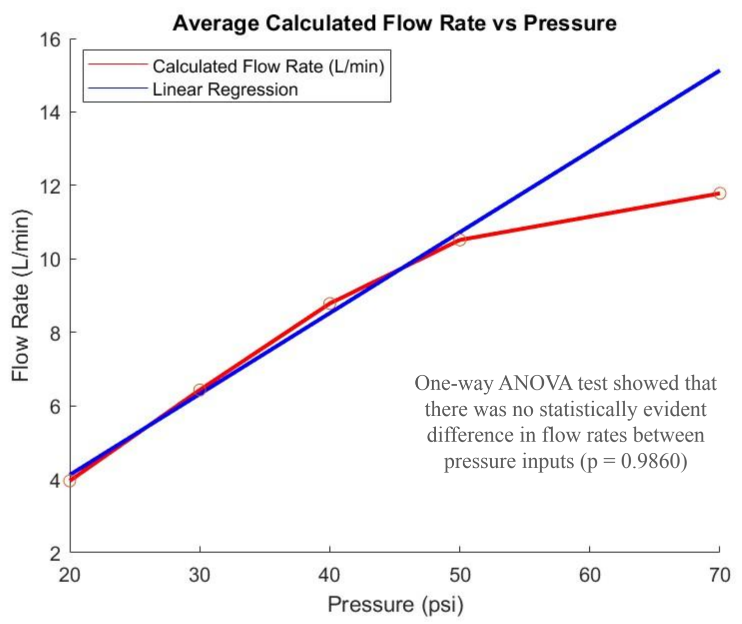

Figure 7: Flow rate vs pressure calibration curve.

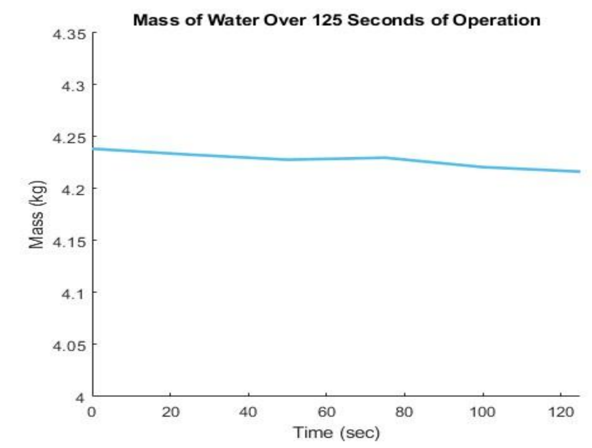

Figure 8: Mass of water (kg) during 125 seconds of operation. Water leakage rate of 0.09 grams/sec.

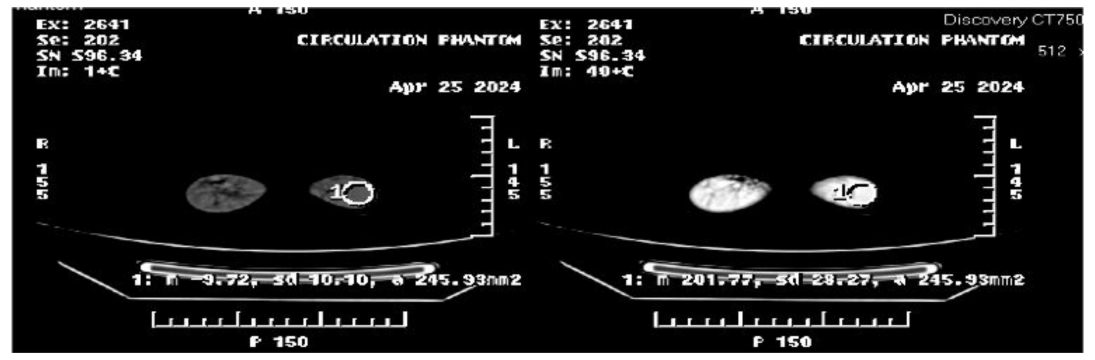

Figure 9: Side by side CT images of the phantom. The left image is prior to addition of the contrast agent, the right image is after.

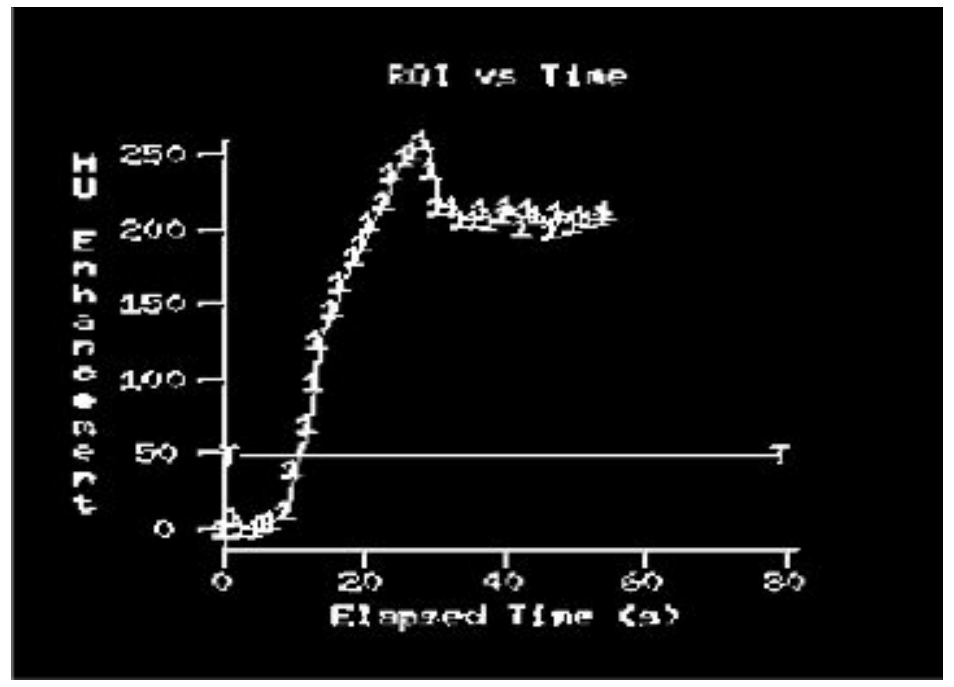

Figure 10: This plot features the temporal variation in relative Hounsfield Units for the region of interest in the scans in Figure 6.

Future Work

- Integrate a separate pulsatile pump to imitate partial heart function
- Incorporate a mechanism to simulate perfusion of contrast agent into other organs resulting in a more drastic decrease in the Hounsfield Unit ROI plot
- Incorporate a blood-like liquid to simulate the viscosity of circulation in a real-life patient
- Fabrication of the aorta model should be reattempted with an acrylic blow mold process

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Conclusion

- Given the resources, time, and budget the device was satisfactory to the clients needs
- Future work needs to be done to improve the precision and accuracy of the device

References

[1] Shen, MD, Jody, Justin Ruey Tse, MD, Frandics Chan, MD, PhD, and Dominik Fleischmann, MD. "CT Angiography of Venoarterial Extracorporeal Membrane Oxygenation." *Stanford University School of Medicine, Department of Radiology*, Cardiac Imaging, February 12, 2022, 16.

[2] Choi, Min Suk, Kiick Sung, and Yang Hyun Cho. "Clinical Pearls of Venoarterial Extracorporeal Membrane Oxygenation for Cardiogenic Shock." *Korean Circulation Journal* 49, no. 8 (July 10, 2019): 657–77. https://doi.org/10.4070/kcj.2019.0188.

[3] "CT Scan - Mayo Clinic." Accessed October 11, 2023. https://www.mayoclinic.org/tests-procedures/ct-scan/about/pac-20393675.

[4] "Poiseuille's Law." Accessed: Dec. 07, 2023. [Online]. Available: https://sciencedemonstrations.fas.harvard.edu/presentations/poiseuilles-law

[5] V. Streeter, *Fluid Mechanics*, vol. 3rd ed. McGraw-Hill, 1962.

[6] A. G. Gheorghe *et al.*, "Cardiac left ventricular myocardial tissue density, evaluated by computed tomography and autopsy," *BMC Med. Imaging*, vol. 19, p. 29, Apr. 2019, doi: 10.1186/s12880-019-0326-4.

[7] M. H. Olsen, T. Thonghong, L. Søndergaard, and K. Møller, "Standardized distances for placement of REBOA in patients with aortic stenosis," *Sci. Rep.*, vol. 10, no. 1, p. 13410, Aug. 2020, doi: 10.1038/s41598-020-70364-9.

[8] D. N. Ku, "BLOOD FLOW IN ARTERIES," Annu. Rev. Fluid Mech., vol. 29, no. 1, pp. 399–434, 1997, doi: 10.1146/annurev.fluid.29.1.399.

[9] Ki, Katrina K., Margaret R. Passmore, Chris H. H. Chan, Maximilian V. Malfertheiner, Jonathon P. Fanning, Mahé Bouquet, Jonathan E. Millar, John F. Fraser, and Jacky Y. Suen. "Low Flow Rate Alters Haemostatic Parameters in an Ex-Vivo Extracorporeal Membrane Oxygenation Circuit." *Intensive Care Medicine Experimental* 7 (August 20, 2019): 51. https://doi.org/10.1186/s40635-019-0264-z.