Computed Tomography Circulation Phantom to Assess Hyperdynamic Contrast Flow Rates

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Client: Dr. Giuseppe Toia; Advisor: Dr. Chris Brace

Abstract

Context

- Veno-arterial extracorporeal membrane oxygenation (VA-ECMO) is a life-support system that circulates and oxygenates blood, similar to the heart and lungs
- Computed Tomography (CT) is a non-invasive imaging technique that aids in patient diagnosis
- During a CT scan, contrast fluid is often injected into a patient's bloodstream to enhance image quality

Problem

- Due to complex blood flow conditions in VA-ECMO patients, radiologists cannot obtain accurate CT scans for patient diagnoses

Solution

- Design a phantom aorta circuit to replicate VA-ECMO flow conditions and develop a standard of practice for injecting contrast into VA-ECMO patients

Key Features

- A two-pump fluid circuit representing the heart and VA-ECMO
- Anatomically accurate circuit with a phantom aorta

Testing & Analysis

- Flow and pressure testing to validate circuit reliability and performance
- CT testing to ensure circuit accuracy

Background

The Client

- Dr. Giuseppe Toia, UW-Health Radiologist
- Uses CT scanning to diagnose patients
- Treats patients on VA-ECMO

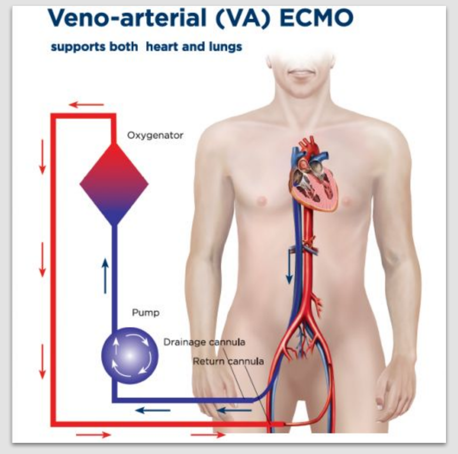

Figure 1: *Diagram of VA-ECMO Circuit [3]*

CT, ECMO, and CT Phantoms

- Cardiovascular and respiratory complications from heart disease have been worsened by COVID-19.
- Computed Tomography (CT)
  - Fast revolving X-rays to produce images inside the body
  - Iodinated contrast for circulatory system scans
- Veno-arterial ECMO (VA-ECMO)
  - For patients with a low cardiac output (<2.2 L/min/m^2)[1]
  - VA-ECMO has an output of 3-5 L/min [2]
  - Life support system, warms, pumps, oxygenates blood of patient and pumps into body via femoral artery
  - Retrograde flow and stagnant contrast fluid create a "watershed area" where VA-ECMO and heart flows meet, complicating CT scan interpretation
- Medical Phantoms
  - Used to mimic physiological conditions
  - Targeted area of CT scan: aortic arch

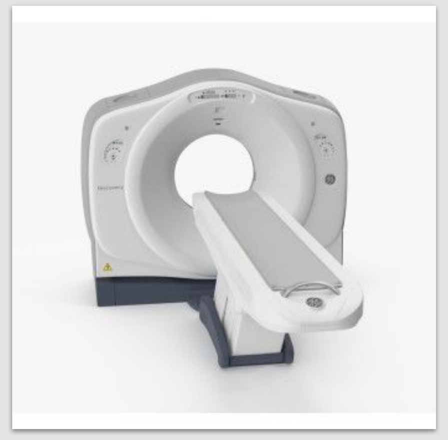

Figure 2: *GE Discovery CT Scanner [4]*

Fundamental Equations

Bernoulli's[5]:

$$P_2 = P_1 + \frac{1}{2}\rho(v_1^2 - v_2^2)$$

P = Pressure
v = Liquid Velocity
ρ= Liquid Density

Flow Continuity[6]:

$$Q = vA$$

Q = Flow Rate
v = Liquid Velocity
A = Area

Thin Wall Cylindrical Pressure Vessel Stress[7]:

$$\sigma_{hoop} = \frac{Pr}{t}$$

σ = Hoop Stress
P = Internal Pressure
r = Inner Radius of Vessel
t = Thickness

Problem Statement

- VA-ECMO procedures have become high in demand due to the respiratory and cardiovascular complications related to COVID-19
- Contrasting flow rates in VA-ECMO patients reduces the effectiveness of contrast fluid in highlighting target areas
- Radiologists need a standard of practice for contrast injection of VA-ECMO patients
- The client, Dr. Giuseppe Toia, has requested a phantom that mimics the human circulatory system and the conditions produced by VA-ECMO to help solve these problems

Design Criteria

- Anatomically accurate
- Two-pump system with contrasting flow rates
- Reservoir to simulate the dilution of contrast in the human body
- Variable pulsatile pump acting as the heart that allows for multiple flow rates between 0 L/min and 6 L/min
- Target area should be the aorta and surrounding tubing that simulates the arteries around the heart
- Operate at a sustained pressure of 270 mmHg for 30 min
- Should not leak more than 5.4 mL/min
- Operate and fit into a CT machine
- Budget: $200

Results and Discussion

1. Flow Test

Measured flow as a function of pressure (VA-ECMO Pump) or dial number (Heart Pump). With the equations to the right, a pressure or dial setting can be inputted to find the associated flow rate.

$$Q = -24398 + 9848\ln(x)$$

Figure 6: *Flow Rate of VA-ECMO from VA-Ecmo pump pressure*

$$Q = 164x + 144$$

Figure 7: *Flow Rate of Heart Pump from dial setting (1-10)*

2. Pressure Test

A pressure gauge was placed within the circuit to find the pressure associated with various Heart and VA-ECMO Pump flow rates. These values were then used to calculate the pressures at the ascending and descending aorta.

3. Leak Test

- Circuit ran 30 minutes at a pressure of 270 mmHg.
- 21 mL of water leaked during this period
- 9x less leakage than the previous group
- Previous group leakage: 0.09mL/s
- Current group leakage: 0.01mL/s

VA-ECMO Flow Rate (L/min)	Heart Flow Rate (L/min)	Net Flow Rate (L/min)	Pressure Gauge (kPa | psi)	Ascending Aorta (kPa | psi)	Descending Aorta (kPa | psi)
2.3	1.8	0.5	25.00 | 3.63	**25.00 | 3.63**	**24.99 | 3.62**
6.0	0.72	5.28	31.02 | 4.50	**31.70 | 4.60**	**30.53 | 4.43**
6.0	1.8	4.2	40.63 | 5.90	**41.06 | 5.96**	**40.32 | 5.85**

Figure 8: *Resultant pressures at the ascending and descending aorta as a result of varying flow rates from the Heart and VA-ECMO Pumps*

4. CT Test

Several CT scans were performed on the phantom aorta and produced the attenuation curves below. The model was placed into the CT machine and iodinated contrast fluid was injected into the circuit.

Figure 9: *Completed circuit on the CT bed*

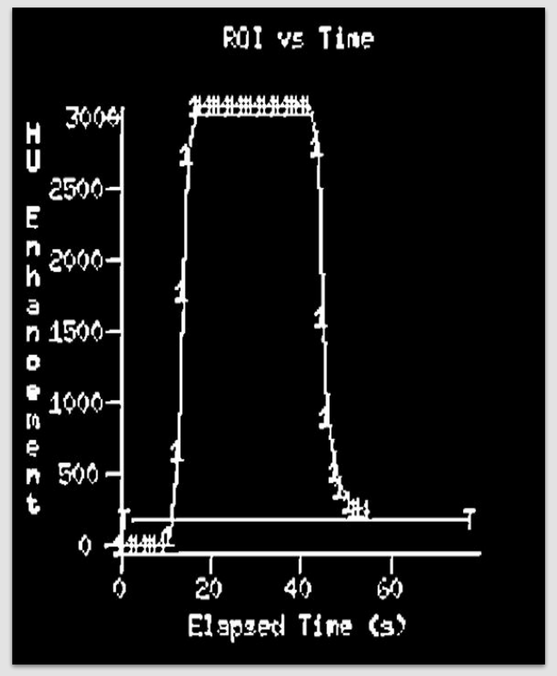

Figure 10: *Attenuation curve of VA-ECMO pump at high flow rate(6L/min) and Heart pump at low flow rate(0.72L/min)*

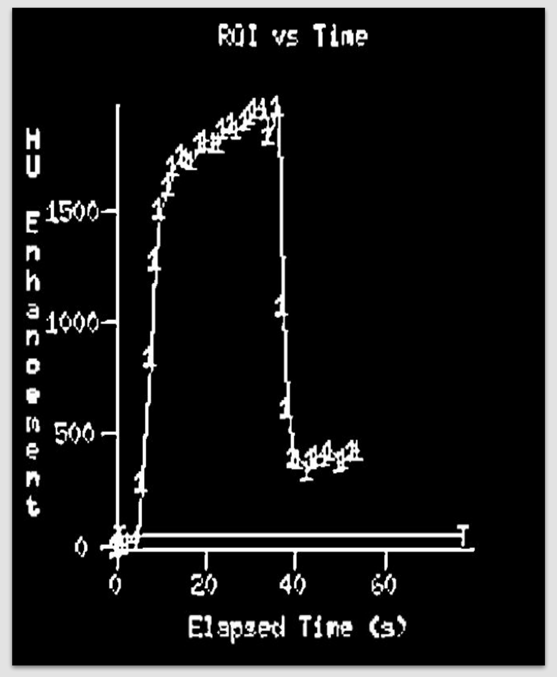

Figure 11: *Attenuation curve of similar flow rates between the Heart(1.8L/min) and VA-ECMO(2.3L/min) pumps*

Final Design

Figure 3: *Phantom Aorta CAD Model*

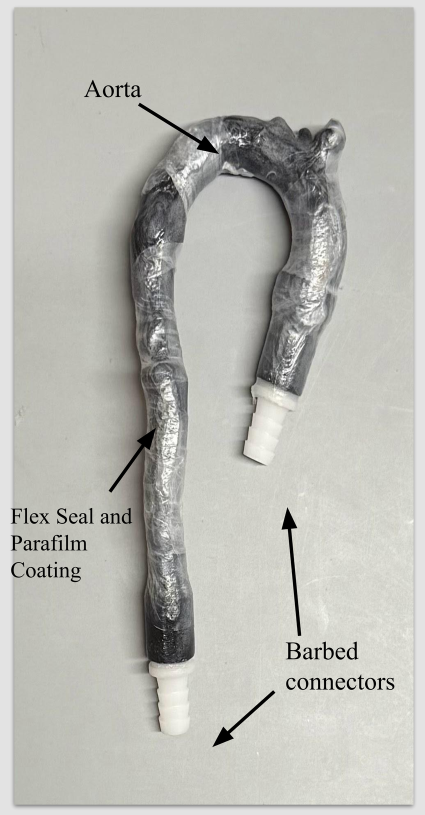

Figure 4: *Fabricated Phantom Aorta*

Key Specifications:

- CAD from CT scan of aorta
- 1:1 scale of human aorta
- 3D-Printed with TPU 95A
- Flex Seal and Parafilm sealant
- Mass attenuation coefficient similar to soft tissue [8, 9]
- Tensile strength: 27.3 MPa [9]
- P_{max} = 3599.06 kPa (522 psi)
- Factor of Safety = 100

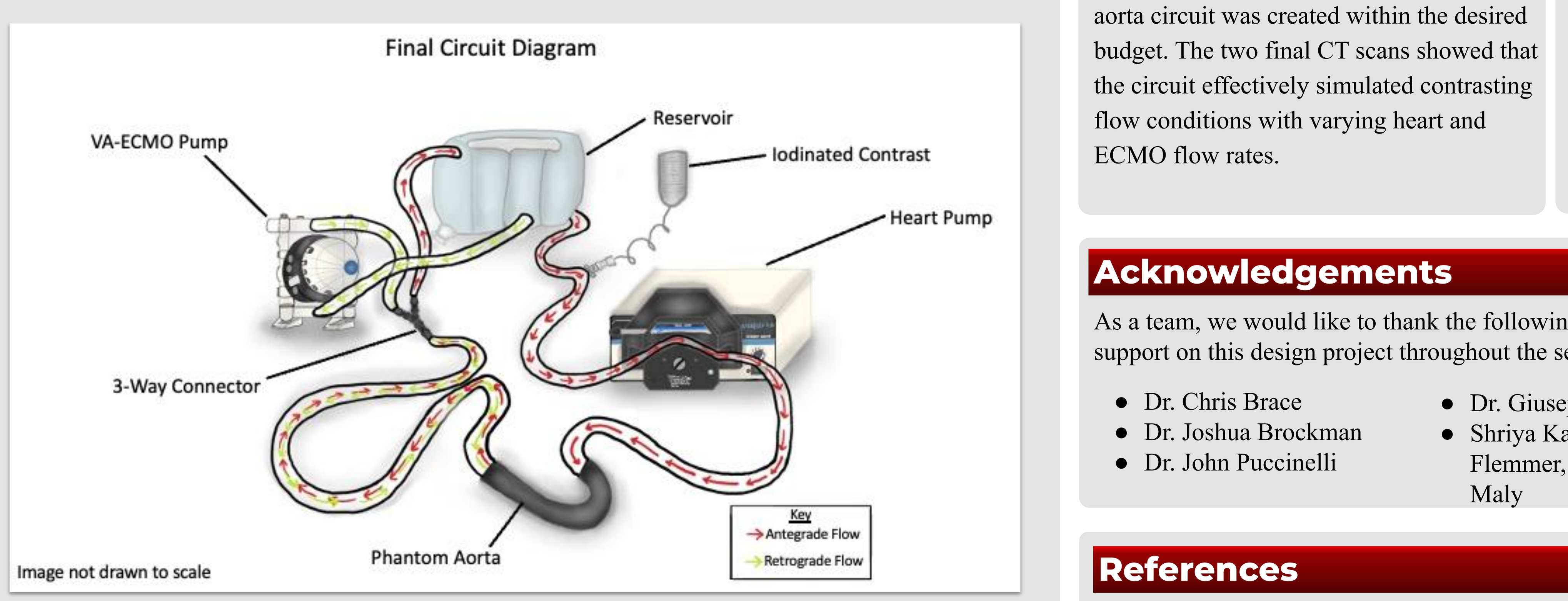

Figure 5: *Final Circuit Diagram*

Phantom Aorta - Target area where cross sections were taken during CT scan
VA-ECMO Pump - Graco Husky 515 Air-Diaphragm pump
Heart Pump - Cole Parmer Masterflex L/S Economy Drive peristaltic pump
Reservoir - Water reservoir simulating dilution created by the body
3-Way Connector - Models the junction of the femoral artery and VA-ECMO input
Iodinated Contrast - Fluid to enhance visibility of phantom aorta during CT scan
Antegrade flow - The normal direction in which blood flows due to the pumping of the heart
Retrograde flow - The direction of blood flow in the opposite direction to anatomical flow caused by VA-ECMO

Conclusion

A two-pump, contrasting flow phantom aorta circuit was created within the desired budget. The two final CT scans showed that the circuit effectively simulated contrasting flow conditions with varying heart and ECMO flow rates.

Future Work

- Use a low-output, pulsatile pump for the Heart Pump and a high-output, linear flow pump for the VA-ECMO Pump
- Use a different method of fabrication for the aorta

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