CARDIOVASCULAR ENGINEERING RESEARCH : DEVELOPMENT OF A MAGNETICALLY-DRIVEN VENTRICULAR ASSIST DEVICE

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BACKGROUND

Currently, over 5 million people in the United States alone suffer from heart failure [1]. This led to the development of a bridge to transplantation device, or Left Ventricular Assist Device (LVAD), that would provide patients more time while waiting for a viable transplant. Although the LVAD has proven to be a successful medical device, the formation of thromboembolisms is still a major health risk. A thrombus, or particulate matter, can form inside the LVAD due to the rotary function of its moving parts.

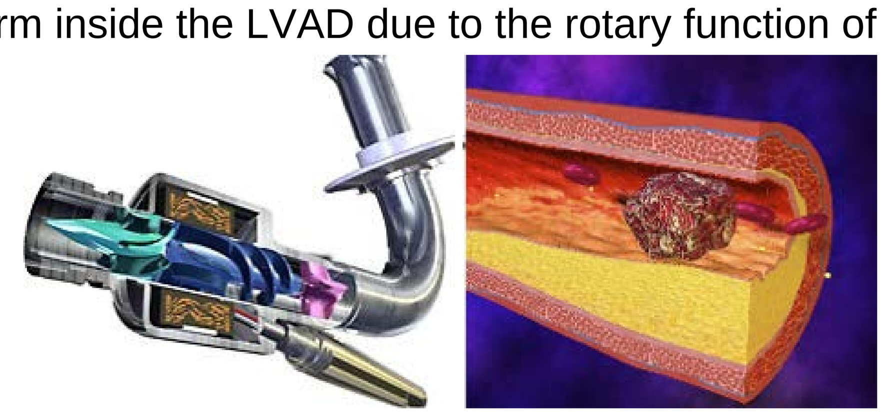

Figure 1: DeBakey continuous flow LVAD (Left), Thrombus inside an artery (Right)

Around 8% of all newborns with a Congenital Heart Defect (CHD) have a single functioning ventricle which is a condition known as Hypoplastic Left Heart Syndrome (HLHS). The Fontan operation has served as the 3rd stage palliation for this anomaly for decades but the surgery entails multiple complications and survival rate is less than 50% by adulthood.

GOAL

Develop a magnetically-driven ventricular assist device without moving parts that will provide assistance to the Fontan cardiovascular circulation.

METHODS

The design of the magnetically-driven ventricular assist device (MVAD) consists of two parts: an electromagnet and ferro-fluid. The MVAD will be tested within the mock circulatory loop which simulates the circulatory system of a 10-year-old male who received the Fontan surgery for Hypoplastic Left Heart Syndrome as an infant.

The electromagnet will be made to produce a magnetic field in order to increase the velocity of the flow. The velocity field *u* of the fluid domain is governed by the Navier-Stokes equations such that,

$$\rho\left(\frac{\partial u}{\partial t} + u.\nabla u\right) = -\nabla p + \boldsymbol{F} + \mu(\nabla^2 u) \qquad (1)$$

Where ***F*** is the Volumetric Body Force exerted on the fluid. In the case of this experiment, the MVAD produces this body force as a result of the magnetic field acting on the ferrous nanoparticles. The magnetic force can be calculated such that,

$$\boldsymbol{F} = (m \cdot \nabla)\boldsymbol{B} \qquad (2)$$

Where m is the magnetic dipole moment and B is the magnetic flux density provided by the inductance of the electromagnetic coil. The magnetic flux density is directly proportional to magnetic intensity with permeability constant, for a particular medium, where,

$$\boldsymbol{B} = \mu H \qquad (3)$$

Using these concepts, the magnetic flux density provided by the electromagnet as,

$$\boldsymbol{B} = \mu \boldsymbol{H} + \boldsymbol{B_{rem}} \qquad (4)$$

Where B_{rem} is the remnant flux density.

A Ferro-fluid is produced using an appropriate ratio of Ferrous Chloride ($FeCl_2$) and Ferric Chloride ($FeCl_3$) solutions mixed together in a base solution of ammonia (NH_3). The solution is kept at a steady temperature of around 50 degrees Celsius by resting on a hot plate under constant homogenization. Oleic Acid is used as a surfactant to inhibit clumping. The solution is centrifuged to eliminate ammonium hydroxide and to segregate the magnetite particles. The excess liquid is then replaced with Polyethylene Glycol (PEG).

ABSTRACT

The current state of the art device used to aid patients with end stage heart failure, Left Ventricular Assist Device (LVAD), still exhibits risks that cause thromboembolisms to enter the bloodstream, which can lead to strokes and death. These risks occur due to the rotary function and small moving parts of the LVAD which cause particulate matter in the blood to form thrombi.

The proposed Magnetically-Driven Ventricular Assist Device (MVAD) will remove the existence of moving parts while still increasing momentum in blood flow. The development of the MVAD consists of an electromagnet and a ferro-fluid that will be tested on the mock circulatory loop. The mock circulatory loop has been calibrated to the anatomical values of an infant with Hypoplastic Left Heart Syndrome.

The synthesis of the ferro-fluid has resulted in average particle diameters of 147 nm, which are used in concentrations of 10%, 25%, and 50%. The sensors of the mock circulatory loop have been calibrated to account for the addition of the ferro-fluid solution instead of water. The electromagnet prototypes will be wrapped in multiple layers of about 45 wraps in each layer.

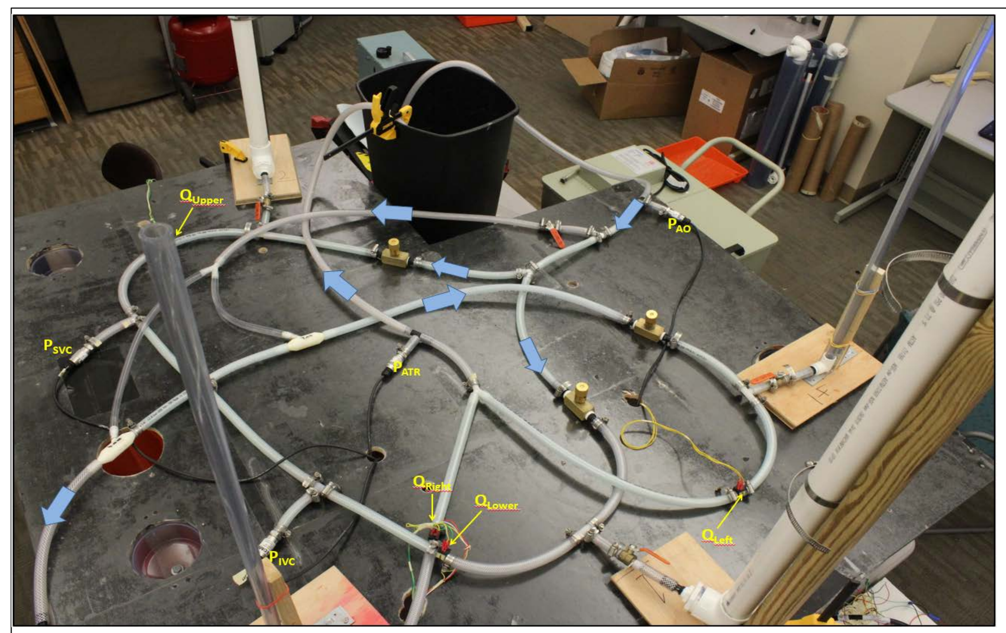

Figure 2: Mock Circulatory Loop

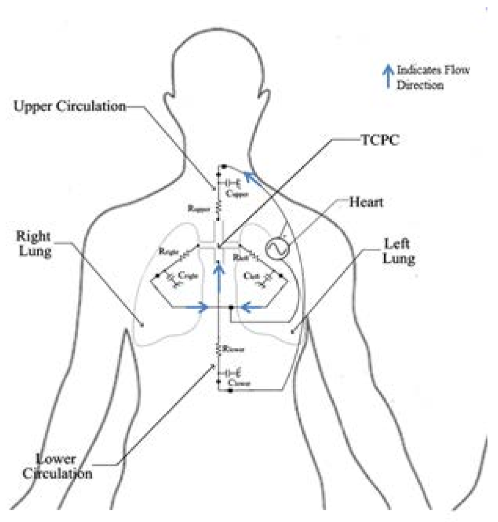

Figure 3: Lumped Parameter Model of the Body

Figure 4:Separation of ammonium hydroxide post-centrifuge.

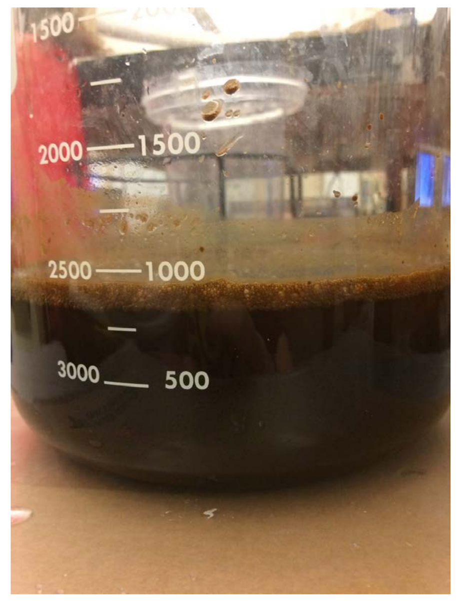

Figure 5: Mixture of ferro-fluid solution at 50% concentration.

Figure 6: Electromagnet prototype with layered wraps of 28 gauge magnet wire.

RESULTS

The diameter of the ferro-fluid particles was determined by placing a sample of the solution onto asilicon wafer for an examination in a Scanning Electron Microscope (SEM), which on average was 147 nm. The ferro-fluid sample was sputter coated with gold particles. For further investigation, the sample was put under a localized Energy-dispersive X-ray spectroscopy (EDX).

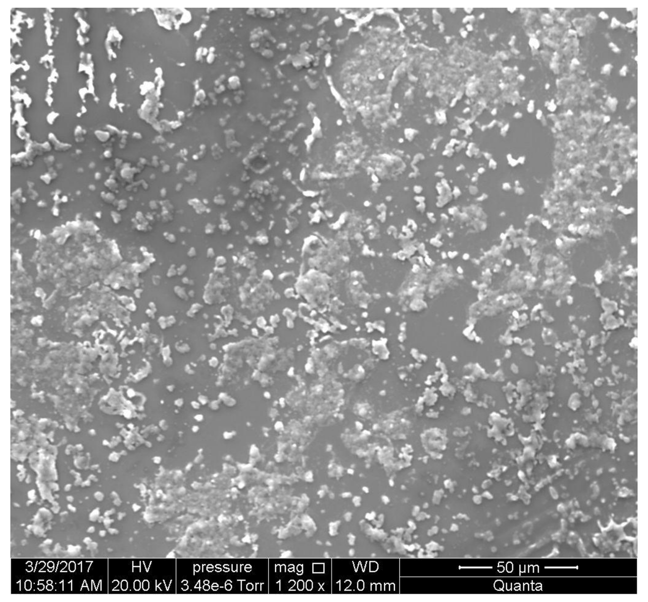

Figure 7: Sample under SEM with Quanta of 50 μm and magnification factor of 1200.

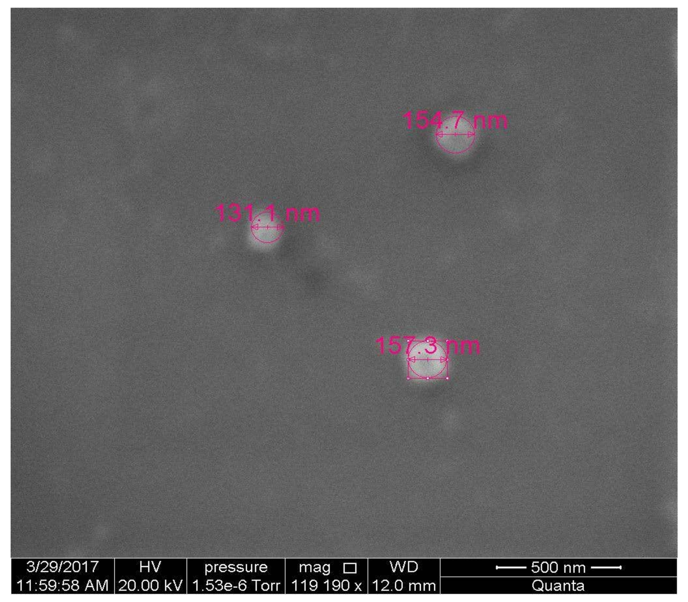

Figure 8: Nanoparticles under SEM with magnification factor of 119190.

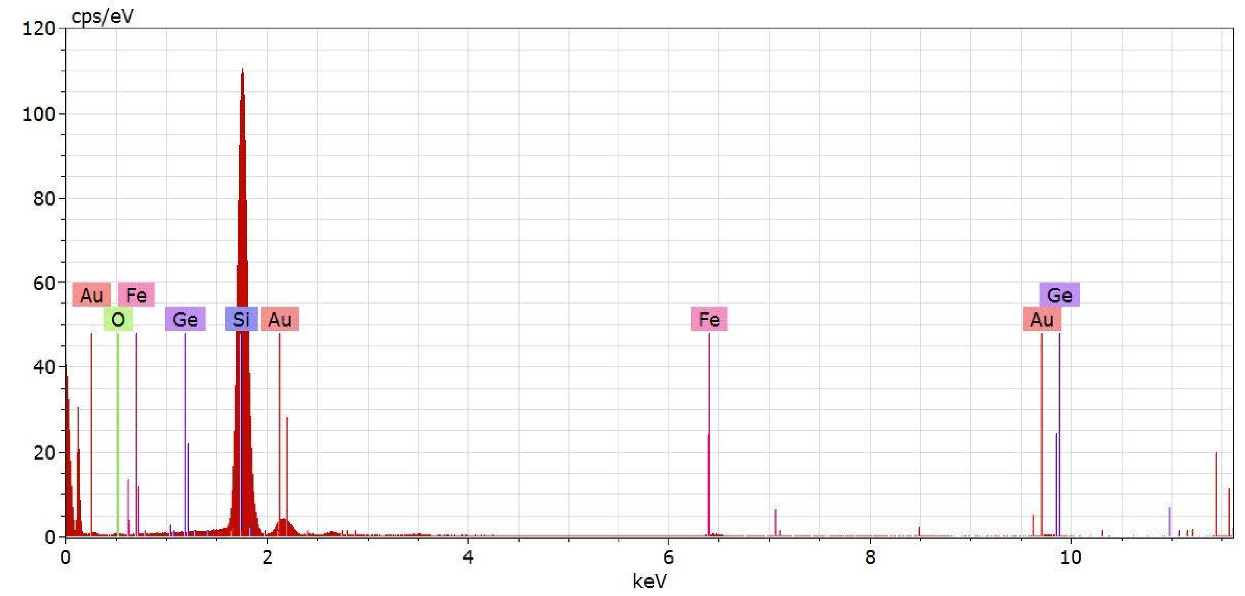

Figure 9: Distribution of elements present in EDX sample along with their energy levels.

It was determined that by wrapping several layers of coils, each layer wrapped around the previous layer with wires in parallel circuits to another, one could achieve high Gauss ratings within the fluid domain at lower power requirements.

Layer	Turns	1.5 A	2.5 A
1	50	28.8 G	43.3 G
2	47	47.4 G	77.6 G
3	44	67.2 G	113.5 G
4	42	85.6 G	144.0 G

Figure 10: Electromagnet Prototype Magnetic Flux with multiple layers

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[2] Pal JD, Piacentino V, Cuevas AD, Depp T, Daneshmand MA, Hernandez AF, Felker GM, Lodge AJ, Rogers JG, Milano CA.,"Impact of left ventricular assist device bridging on posttransplant Outcomes," Ann Thorac Surg., 2009 Nov;88(5):1457-61; discussion 1461.

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