

**Exploring How to Merge an Aspiration Thrombectomy Device and a Rotational
Atherectomy Device For Efficacious Individual or Joint Removal of Thrombi and Plaque
Through In-Vitro Testing**

Word count: 5,253

Abstract

Endovascular occlusive diseases are among the leading causes of death around the world. Specifically, thrombosis is responsible for 1 in 4 people dying worldwide. Atherosclerosis is the cause of over 50% of deaths in westernized society. The purpose of this research was to improve on existing atherectomy and thrombectomy technology by producing a device that can conduct an atherectomy or thrombectomy independently or simultaneously. The goal of this research was to design, construct, and test an efficacious and safe joint rotational atherectomy and aspiration thrombectomy device. The device was designed using 3D models and constructed using balsa wood, metal tubes, DC-motors, 3D-printed parts, wires, batteries, and surgical tubes. To test the device, a mock aspiration thrombectomy and rotational atherectomy were performed in a model blood vessel using model blood clots and plaque, respectively. The joint device was successful and increased the lumen diameter of blood vessels obstructed with blood clots or plaque. The mass of the blood clot present within the model blood vessel decreased, on average, from 206.66 grams to 0.00 grams, meaning 100% of the blood vessels were cleared. The plaque lumen diameter increased, on average, by 346.67% by the end of each procedure. It was concluded that such a joint device can effectively remove blood clots and plaque from blood vessels simultaneously or independently from relatively large blood vessels and is applicable in medical institutions.

Introduction

Endovascular occlusive diseases, such as thrombosis and atherosclerosis, are among the leading causes of death around the world. Thrombosis is characterized by the formation of blood clots, which can result in abnormal blood flow throughout the human vascular system.

Thrombosis is responsible for 1 in 4 people dying worldwide (“Thrombosis,” n.d.).

Atherosclerosis is a disease characterized by the buildup of cholesterol, fats, calcium, and other substances in and on artery walls. The buildup can block or narrow arteries, restricting the flow of blood. Atherosclerosis is the “underlying cause of about 50% of all deaths in westernized society” (Pahwa & Jialal, 2010, para. 1).

Blood clots are primarily composed of fibrin and platelets. Thin fibers are located throughout the blood clot forming a dense support network. Blood clots usually form in arteries when blood is exposed to procoagulant components, such as “collagen and lipid-rich activated macrophages” (Chernysh et al., 2020, p. 1). The formation of venous blood clots is a result of hypercoagulability and injured endothelium tissue (Chernysh et al., 2020). A common treatment option for thrombosis is the use of thrombolytic agents. It involves using medications to dissolve blood clots. However, thrombolytic agents have shown to have limited effectiveness in treating subacute and chronic thrombus. According to Behrens and Bjarnason, radiologists at Hinsdale Adventist Hospital and Mayo Clinic, respectively, this has resulted in a search for better methods of thrombus removal (2015). Since 1995, several new methods and tools for the removal of large venous thrombus have been introduced (Behrens & Bjarnason, 2015). One novel method is the use of catheter-based thrombus removal devices. These minimally-invasive catheter-based devices utilize aspiration, fragmentation, extraction, or liquid pressure jets to achieve thrombus removal (Behrens & Bjarnason, 2015). The proposed experiment focuses on aspiration

thrombectomy devices, which use negative pressure to directly suction and capture fresh, soft thrombi (Spiotta et al., 2014).

Arterial plaque forms when there is an increased blood concentration of apolipoprotein B, which contains lipoproteins (Bentzon et al., 2014). Blood clots and plaque can be found in the same blood vessel for patients with coronary artery disease. This is because arterial plaque can rupture and expose blood to procoagulant components, resulting in a blood clot (Chernysh et al., 2020). Common treatment options for atherosclerosis are the use of balloons, stents, and permanent devices, which increase the lumen size and support the inside of a calcified blood vessel to prevent further vascular occlusion. Although stents have better overall durability compared to simple balloon angioplasty, there is no single device that “has evolved as the default gold standard,” for longer and heavily calcified lesions (Bhat et al., 2017, p. 135). Furthermore, according to Bhat et al., stents or any permanent device over joint spaces have the risk of causing stent cell strut fracture, which can lead to stent failure (2017). As a result of this limitation, Bhat et al., claims that attempts are being made to develop a therapeutic option that does not use permanent implants in the vessels (2017). Atherectomies have emerged as a viable alternative for the treatment of atherosclerosis. An atherectomy is the endovascular removal of plaque by drilling or pulverizing plaque (Bhat et al., 2017, p. 135). The proposed experiment focuses on the use of rotational atherectomy devices, which utilize a high-speed rotating burr to grind away at plaque while preserving blood vessel walls.

Being a relatively new field of biomedical technology and research, there remains much to be learned about the use of endovascular devices for clearing vascular occlusions. In terms of efficacy and safety, there are no devices available today that can effectively remove 100% of the obstructions safely (Bhat et al., 2017). However, many of the studies agree that a combination of

already existing catheter-based, endovascular devices may lead to a more efficacious and safe treatment option (Bhat et al., 2017; Chueh et al., 2012; Spiotta et al., 2014). Therefore, the proposed experiment attempts to explore how to merge an aspiration thrombectomy device with a rotational atherectomy device for the removal of thrombi and plaque. The device should be able to clear both occlusions if present in the same or different blood vessels. In addition, the device should be safe by preventing the downstream flow of vascular debris and by keeping the rotating burr away from blood vessel walls. In the proposed experiment, such model joint device was designed and constructed; it was then tested for efficacy and safety in a model blood vessel using models of blood clots and plaque.

Currently, very few joint devices have the capability to remove both plaque and thrombus. Besides the efficacious and safe removal of thrombi and plaque, there are a multitude of benefits for designing a joint, catheter-based endovascular device. According to Dr. Siddique, a cardiac electrophysiologist at Palmetto Heart/Health, if a patient is suffering from both types of occlusions in the same blood vessel, joint devices have the capability to remove the blood clot and plaque in one intervention (S. Siddique, personal communication, August 22, 2020). More than one intervention for the treatment can mean the patient is in surgery for a longer time, which increases the chance of adverse events occurring (Ascher et al., 2019). In addition, atherectomy and thrombectomy require two different devices, meaning the surgeon has to be professionally trained for both devices. According to Dr. Morgan, a cardiologist and cardiovascular disease specialist at Providence Health, having one device that can perform both procedures can help medical institutions save money training doctors and buying equipment (G. Morgan, personal communication, December 9, 2020). Overall, this reveals that the gap in the current field of knowledge exists for a joint device that will both increase the efficacy and safety of endovascular

occlusion-clearing procedures as well as benefit the patients, doctors, and medical institutions involved in the procedures.

Literature Review

There are a multitude of perspectives and approaches researchers have assumed in the past when trying to advance endovascular devices.

One approach involves improving the designs of already existing single-type atherectomy and thrombectomy devices. In a clinical study by Ritchie et al., the authors describe the design of the novel catheter-based atherectomy device as follows (1986). A blunt platinum radio-opaque tip was bonded to a flexible steel wire and the proximal end of the wire was attached to an air-driven motor that can be rotated at 4000 rotations per minute (rpm) (Ritchie et al., 1986). The authors of the study tested the novel device design using acute thrombosis in vitro and in vivo. For testing in vitro, the authors measured the pressure required to penetrate a model blood clot with the novel rotational catheter. For testing in vivo, an atherectomy was performed on Mongrel dogs (Ritchie et al., 1986). According to the conclusion of the study, the authors claim that the novel device design enhances the penetration of acute thrombus.

A few studies have explored combining currently available devices with novel catheter designs for improved delivery of the device. In a case study by Vo et al., researchers from the Department of Internal Medicine at the University of Manitoba and Bergen Cardiac Care Center at St. Boniface General Hospital built and tested the use of a novel GuideLiner catheter to deliver rotational atherectomy burrs in tortuous vessels (2014). The GuideLiner is a rapid exchange mother and child guide extension catheter that allows deep intubation of a specific vessel. The first case discussed involved a severe calcification of an artery. A 2.5-millimeter balloon was used to facilitate the advancement of the GuideLiner catheter (Vo et al., 2014). Then, a

1.25-millimeter burr was advanced through the catheter and multiple rotational atherectomy runs were conducted at 160,000 rotations per minute. According to the conclusion of the journal article, GuideLiner and Rotablator are important supportive devices for complex percutaneous coronary intervention cases (Vo et al., 2014). By using the device and novel catheter system, the study expanded the role of each component and successfully treated patients with heavily calcified arteries.

Another perspective explores and tests novel atherectomy or thrombectomy procedural techniques. For example, Yamamoto et al. tested a novel rotablator technique that incorporates pecking motions of a low-speed followed by a high-speed rotational atherectomy (2019). The study, conducted by researchers from the Tokyo Medical and Dental University, involved twenty-nine patients and a single operator for the clinical trials (Yamamoto et al., 2019). The patients received the same drug treatment before the surgery, and the same pecking motion and novel technique was used to perform the atherectomy. According to the findings of the study, the high-speed rotational atherectomy was responsible for allowing the device to pass through the lesion quickly, while the low-speed rotational atherectomy allowed for the larger lumen gain. This novel technique was claimed to be more efficient than the conventional technique, which is only a high-speed atherectomy (Yamamoto et al., 2019).

Other studies have designed novel atherectomy or thrombectomy general protocols, which include the steps from diagnosis to hospital discharge. Ascher et al. successfully tested a fast-track procedure that can reduce both the cost of the procedure and the number of adverse events (2019). The study analyzed 38 patients treated for acute iliofemoral deep venous thrombosis (IFDVT) using the fast-track thrombolysis protocol (FTTP). According to the results of the study, the mean operative time was 122 minutes and the median cost per procedure was

\$5374.45, which is relatively low compared to the standard time and cost. Regarding the long-term effect of the procedure, no patient experienced re-thrombosis within 30 days and no cases of pulmonary embolism, significant hemorrhage, or mortality were seen for 5 years. These positive outcomes indicate that FTTP is a safe, efficacious, cost-effective technique to treat acute IFVDT, and showed that a single intervention approach is possible (Ascher et al., 2019).

These varying perspectives reveal a significant research gap in the efficacious and safe treatment of endovascular occlusions using a joint device. Contrary to the other approaches, a joint device would not combine existing technology with a catheter delivery system, slightly modify the design of catheter-based devices, develop a new protocol for treating endovascular occlusions, or establish a novel procedural thrombectomy or atherectomy technique. Instead, a novel joint device would combine two already existing, successful catheter-based devices in an attempt to develop and improve on the treatment options available today. The purpose of this research was to determine if combining more than one device is a possible path for improving endovascular technology. The engineering goal for this research project was to combine a rotational atherectomy device with an aspiration thrombectomy device for efficacious and safe joint or individual removal of thrombi and plaque. Then, the designed and constructed device was tested in-vitro using a mock blood vessel and model blood clots and plaque.

Materials

Hot glue gun and 6 glue gun sticks	1 - Stainless steel round tube - 5.94 mm outer diameter, 25 mm length
22 Gauge Silicone Electric wire	
Kelvin Switchable direct current Power Supply	150 count Cotton Balls
Tin-lead Rosin Core Solder Wire	947 mL of Water
Soldering iron	Stove
Stopwatch (iPhone)	1 - Latex Water Balloon
Carolina Biological Electronic Scale	Three-Dimensional (3D) Printer
Google Spreadsheets	Polylactic acid 3D printer filament
2 - 6 volt direct current (DC) motors	Measuring cup (mL)
Gear train made of 2 gears: Bore sizes 2.3 mm and 6.3mm, respectively	122 cm plastic tube with 2.5 cm diameter
	120V vacuum motor fan

9V mini air pump	Vacuum tubing
7 mm outer diameter surgical tubing	1mm thick sheet metal
1 - O-ring (6mm outer diameter, 2mm inner diameter)	Polyvinyl chloride (PVC) Expansion Repair Coupling
Refrigerator	

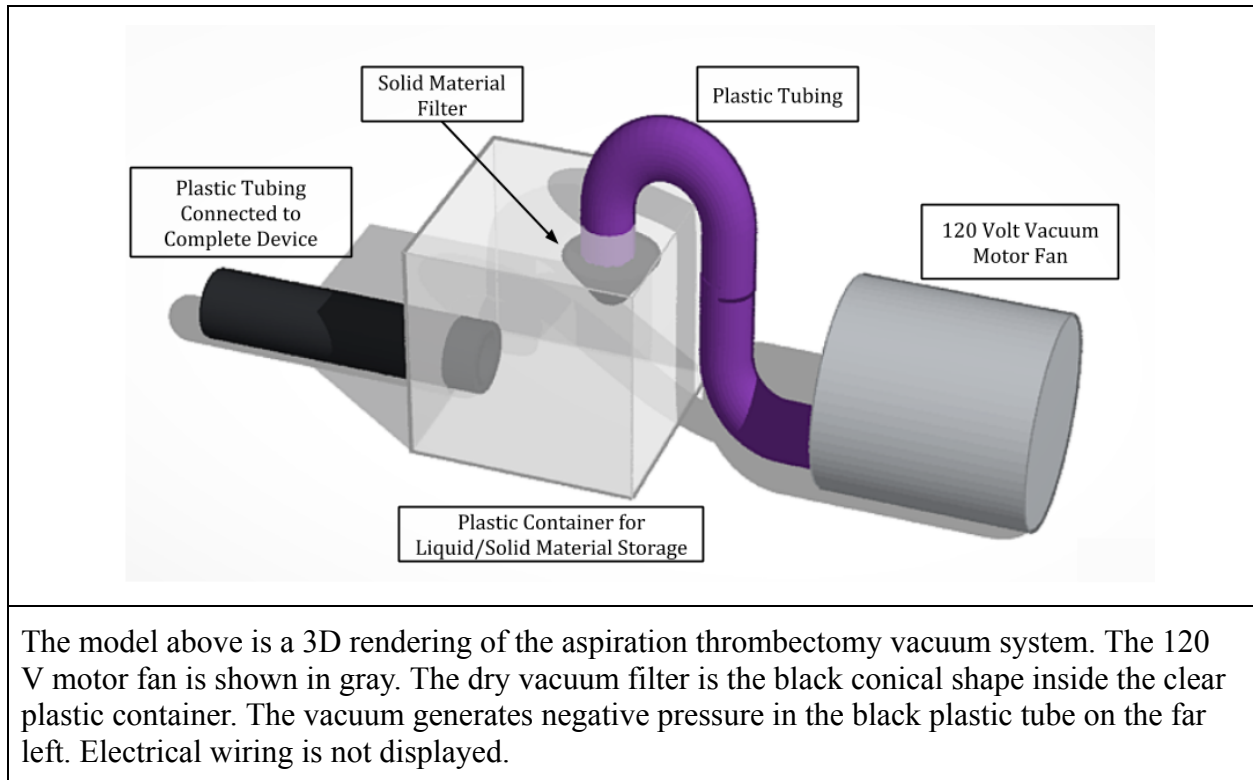
Methods

To explore how to combine a rotational atherectomy device and an aspiration thrombectomy device, the standard engineering process was followed: a prototype was designed, constructed, and tested.

Joint Atherectomy and Thrombectomy Device

The joint atherectomy and thrombectomy device combines an aspiration thrombectomy device with a rotational atherectomy device. Of the many types of thrombectomy and atherectomy devices available, these types were chosen because Reisman et al. (1997) and Przybylowski et al. (2014) found that rotational atherectomy devices and aspiration thrombectomy devices are effective at clearing vascular occlusions and are easy to modify, respectively. An aspiration thrombectomy device utilizes a vacuum to collect vascular debris. The vacuum should be able to suction wet blood clots and plaque. To construct the vacuum, a 120 volt (V) motor fan with a switch and a 14-gauge non-metallic cable, which could be plugged into a wall outlet, were used. To allow the vacuum to suction wet and dry material, a plastic container and vacuum filter were arranged as shown in Figure 1.

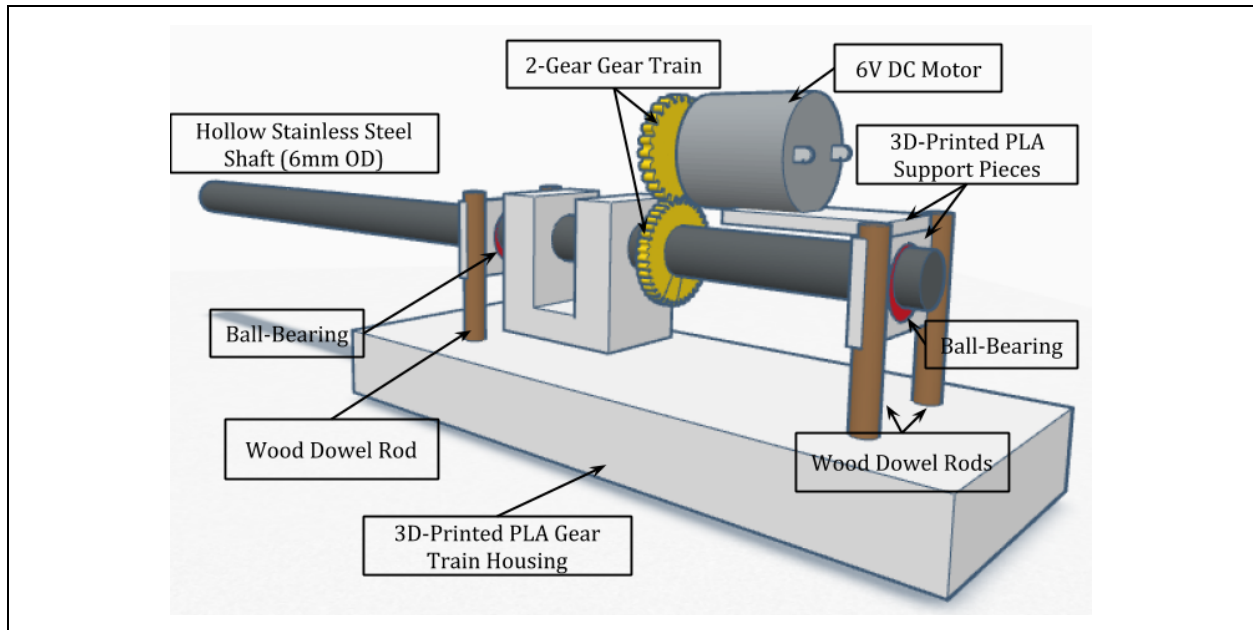
Figure 1. *Aspiration Thrombectomy Vacuum System*



The plastic tubing was securely attached to the plastic container and motor. The suctioned plaque would stay inside the plastic container due to the dry vacuum filter and the blood clot would settle at the bottom of the container due to gravity and low suction power. The vacuum generated negative pressure in the black plastic tube, which was connected to the joint device later.

To construct the model rotational atherectomy device, a stainless steel shaft with an outer diameter (OD) of 6-millimeter (mm) and a length of 25-centimeter (cm) was used. The shaft would be spun at high speeds with a plaque-grinding burr attached to one end. A gear train, composed of two same-sized vertical gears to increase rotation torque, was used to spin the shaft. As shown in Figure 2, the gear train was secured using 3D-printed housing.

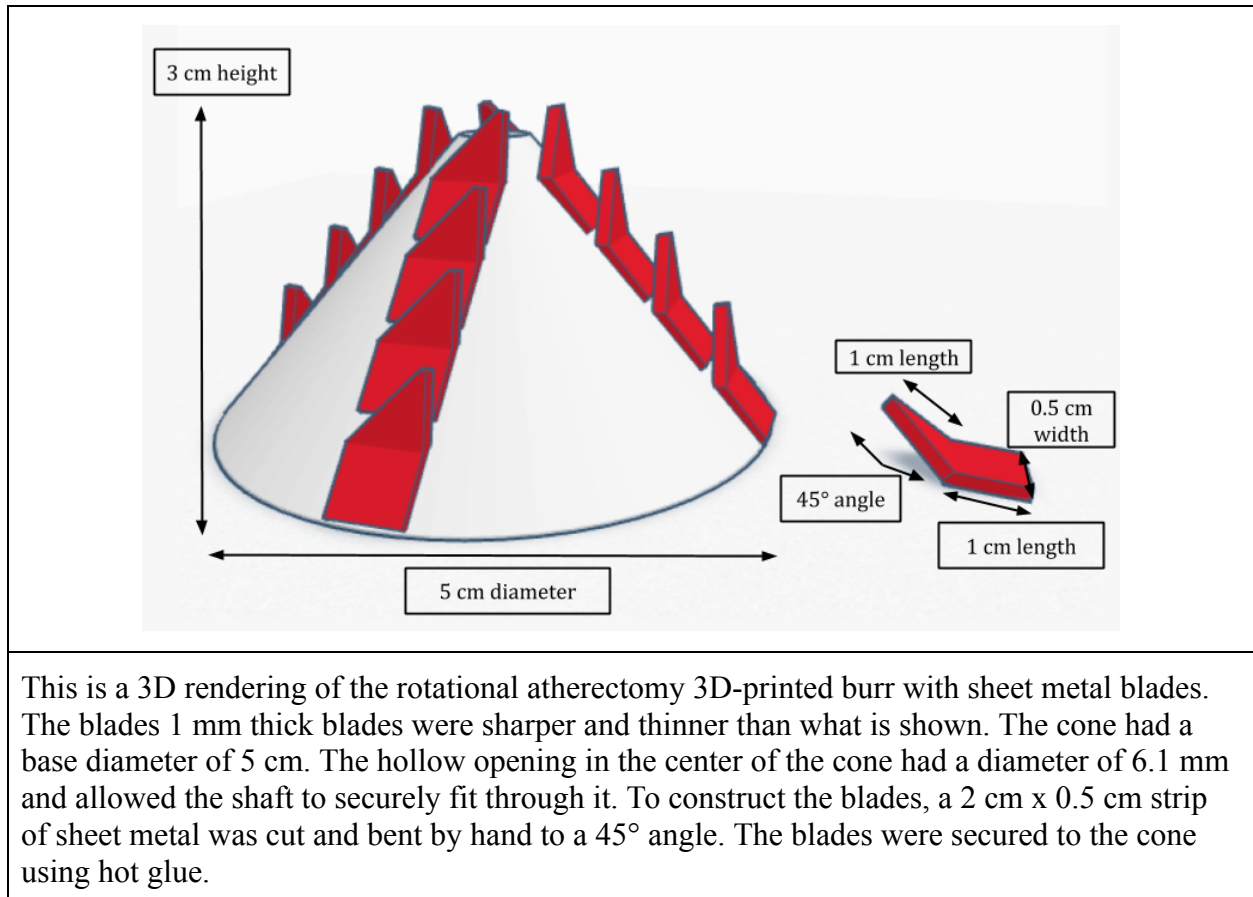
Figure 2. Gear Train and 3D Printed Gear Train Housing



The model above is a 3D rendering of the gear train and the 3D printed gear train housing. The housing secured a stainless steel hollow shaft that had an outer diameter of 5.94 mm. The material used for printing was polylactic acid (PLA) filament. The red circles on the left and right sides are ball bearings that supported the steel shaft when it spun at high speeds. The components in white were 3D printed. The two brown columns are wooden dowel rods. The 6 volt DC motor is shown in light gray. This figure shows the rotational atherectomy component of the joint device. Electrical wiring is not displayed.

The gear train was driven by a 6-volt motor. The stainless steel shaft was further supported by ball bearings. The thrombectomy and atherectomy systems were base components of the joint device and were constructed using available materials to only model the real devices. The burr, shown in Figure 3, was a 3D printed cone with sheet metal blades attached to the surface.

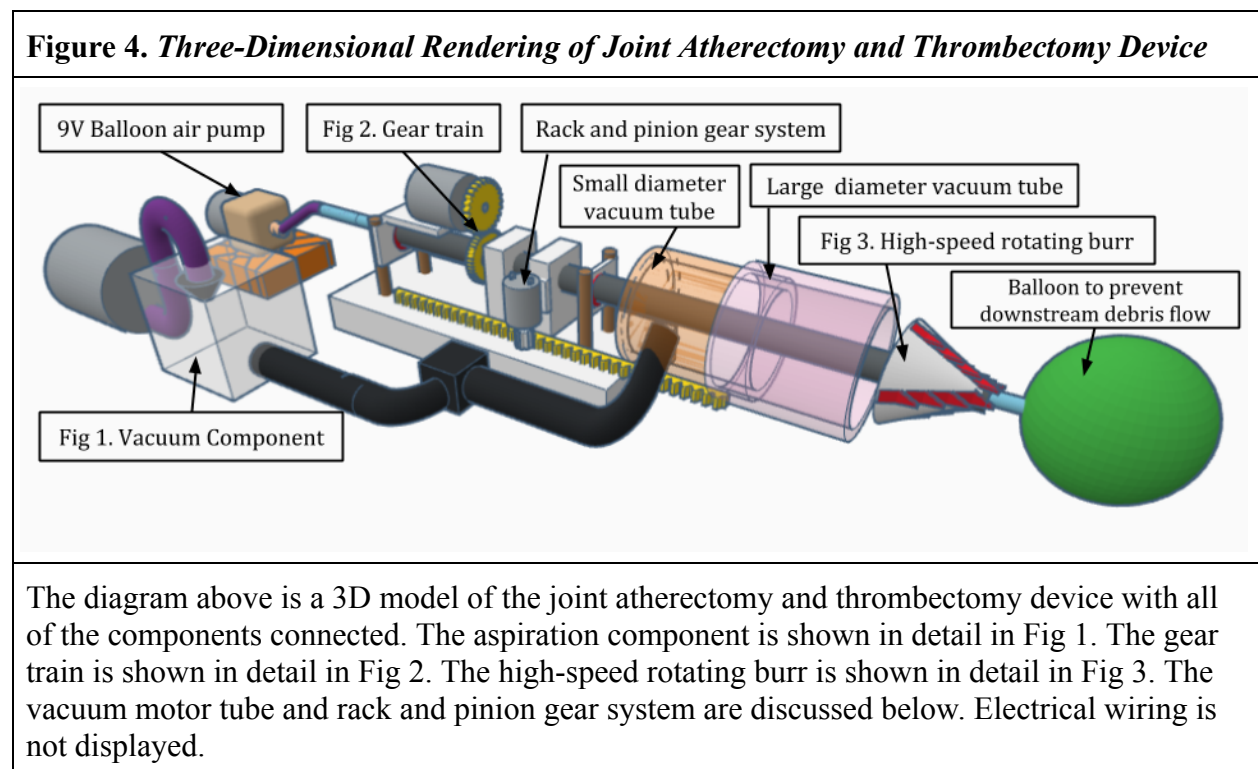
Figure 3. Rotational Atherectomy 3D-Printed Burr with Sheet Metal Blades



An additional safety feature added to the joint atherectomy and thrombectomy device was an inflatable balloon on the distal end of the shaft, following the burr. During an atherectomy or thrombectomy, the endovascular device travels in the same direction of the blood flow (G. Morgan, personal communication, December 9, 2020). As a result, pieces of ground blood clots, plaque, and other vascular debris can flow downstream, leading to adverse events in small-diameter blood vessels. The inflatable balloon was designed to prevent the downstream flow of vascular debris by blocking the vessel during the procedure. According to Dr. Morgan, a blood vessel can be blocked for no more than 30-45 seconds at a time (G. Morgan, personal communication, December 9, 2020). To construct the inflatable balloon, a 9-volt mini air pump was connected to a 7mm OD surgical tubing. The air pump was placed behind the 3D printed gear train housing and the surgical tube was inserted through the hollow stainless steel shaft until

3 cm of the tube was protruding past the burr. A water balloon, modeling an angioplasty balloon, was attached to the other end of the surgical tube using an O-ring with an inner diameter and ring thickness of 2 mm. The balloons used during balloon angioplasty (a procedure used to open narrowed arteries using a balloon) have the tensile strength of steel to ensure safe and successful treatment of the patient (G. Morgan, personal communication, December 9, 2020; Steele et al., 1985).

To construct the joint rotational atherectomy and aspirational thrombectomy device, each of the components was assembled together, as shown in Figure 4.

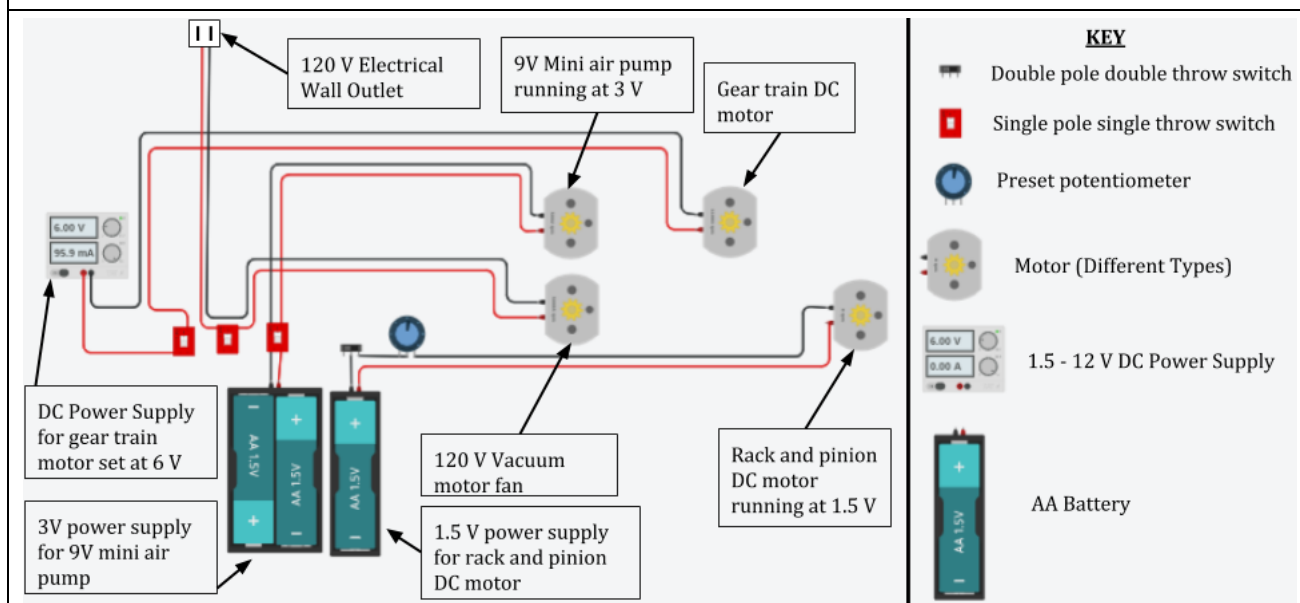


As shown in Figure 4, the vacuum component was connected to a PVC expandable repair coupling so that the negative pressure of the vacuum would be applied directly behind the rotating burr. The expandable coupling, referred to as the vacuum tubes in Figure 4, had two components. Neither of the components spun with the main shaft because they were connected to the shaft using ball bearings. The orange tube in Figure 4, had an inner diameter of 4.5 cm and

was immobile. The pink vacuum tube in Figure 4 had an inner diameter of 6.35 cm and could move back and forth about 3 cm along the stainless steel shaft. The moving tube ensured that all vascular debris was suctioned by the vacuum, making the device more safe. It was an additional safety feature added to the base components of the joint device. The back and forth movement was accomplished using a rack and pinion gear system. In Figure 4, the rack is shown in yellow, attached to the pink pipe. The pinion was connected to a 1.5-volt motor that was glued to the 3D-printed gear train housing. Pictures of all the joint device components can be seen in Appendix B.

All the motors and pumps were wired with an ON/OFF switch after the device was constructed to ensure safe usage of the device. The switches were organized in a wooden switchboard. A circuit drawing of the wiring can be seen in Figure 5. Pictures of the wiring and switchboard can be seen in Appendix A.

Figure 5. Circuit Drawing for Powering the Joint Atherectomy and Thrombectomy Device



The diagram above is the circuit drawing for powering the joint atherectomy and thrombectomy device. The switchboard, not displayed in this diagram, included the double pole double throw (DPDT) switch, the single pole single throw switch (SPST), and the preset potentiometer. The

120V vacuum motor fan was powered by an electrical wall outlet. The gear train direct current motor was powered by a DC power supply set at 6 V. The 9V mini air pump was powered by 2 AA batteries, meaning it was supplied with 3V. The rack and pinion DC motor rotation speed was controlled by the preset potentiometer and powered by 1 AA battery. Instead of an SPST switch, it had a DPDT switch so that the polarity could be reversed and the large vacuum tube could move forward and backward. All of the wire work was completed using a soldering iron, lead-based solder, and 22 gauge silicone electrical wire.

Model Thrombi

Due to limited resources, model thrombi were used to test the joint atherectomy and thrombectomy device in-vitro. According to Tocantins, blood clots are gel-like and “made up of a meshwork of fibrin needles” with some bundles of fibers (Tocantins, 1935, p. 709; Chernysh et al., 2020, p. 1). Specifically, 43% of arterial thrombi volume and 35% of venous thrombi volume make up the fiber network (Chernysh et al., 2020, p. 2). So, blood clots were modeled using materials with similar properties. The primary component of the model blood clot was gelatin; this would represent the gel-like physical property. To make the gelatin, 340.194 grams of dry raspberry Jello powder was added to 473.176 mL of boiling water. This mixture was stirred until the Jello powder was completely dissolved in the water. Next, 473.176 mL of cold water was added to the mixture and stirred. The red color of the Jello made the model blood clot easy to observe during experimentation. To model the fibrin needles and bundles, torn pieces of cotton were placed evenly throughout the Jello solution. Forty-three percent and thirty-five percent were averaged to calculate the average volume of the fiber network in blood clots; so, 39% of the model blood clot volume was cotton balls. The equation shown in Figure 6 was used to determine the volume of cotton balls that were added to the gelatin mixture.

Figure 6. Mathematical Equation Used to Determine Cotton Ball Volume in Model Blood Clot

x = volume of cotton balls added to the Jello solution
 $1286.546 \text{ mL} = \text{Total volume of jello solution (water + dry powder)}$

$$x / (x + 1286.546) = 0.39 \text{ (0.39 = 39\% average thrombi volume made of a fiber network)}$$

$$x = 822.546$$

822.546 mL of cotton balls had to be added to the Jello solution so that the model fibers made up 39% of the model blood clot. To measure out this volume of cotton balls, a measuring cup was used.

Once the 822.546 mL of small cotton ball pieces were evenly placed throughout the Jello solution, the mixture was placed in the refrigerator for 5 hours so that it would become firm.

Figure 7 shows the end result of the model blood clot.

Figure 7. Model Blood Clot Composed of Raspberry Jello Mix and Cotton Balls



The picture on the left shows the model blood clot right after it was taken out of the refrigerator. The picture on the right shows the model blood clot after it was placed in the model blood vessel, discussed later.

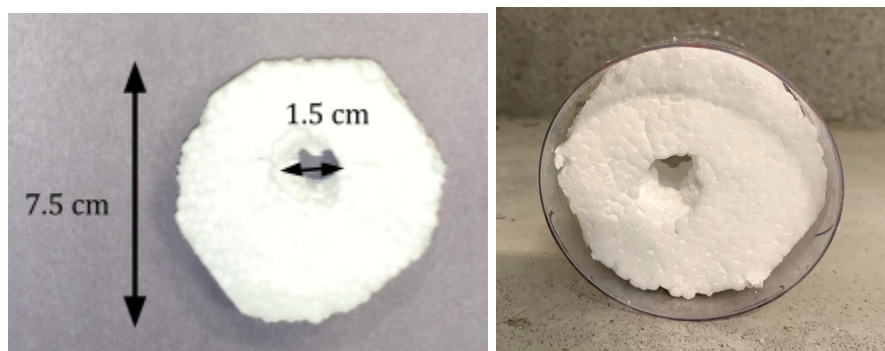
Because 5 trials had to be conducted, the mixture was split into 5 even groups and placed separately inside a model blood vessel, discussed later.

Model Plaque

Due to limited resources, model plaque was used to test the joint atherectomy and thrombectomy device in-vitro. According to Davaine et al., arterial calcification, also known as plaque-buildup, is a process that mimics bone formation (2016). Plaque is hard and similar to mammalian bone tissue on the outer surface and somewhat spongy on the inside (G. Morgan, personal communication, December 9, 2020). To model plaque, packaging styrofoam was cut

and shaped so that it would fit tightly inside a model blood vessel. The hard, outer surface of plaque was not modeled because the constructed joint device lacked power and torque to cut through bone tissue-like material. In the center of the plaque, a small hole, with a diameter of 1.5 cm, was cut to relieve mechanical stress from the joint device during a simulation and to model minute blood flow present in the blood vessel. Figure 8 shows the model plaque.

Figure 8. Pictures of Styrofoam Model Plaque Before Experimentation



This figure shows the model plaque used to test the joint device. The diameter of the model plaque was based on the diameter of the model blood vessel. The width of the plaque was determined based on the maximum width the joint device could cut through due to the physical limitations of the design. The image on the right shows the model plaque placed inside of the model blood vessel, discussed below.

Model Blood Vessel

The model plaque and model blood clot were placed inside of a model blood vessel to test the joint atherectomy and thrombectomy device in-vitro. Blood vessels are tube-like structures that transport blood, so a plastic tube was used to model the blood vessel. A study by Gepstein et al. followed a similar method of using tubing to successfully and accurately test endovascular devices in-vitro (1997). The model blood vessel was a clear, plastic tube 31 cm long with a diameter of 7.5 cm. During experimentation, the model blood clots or model plaque were placed inside of the plastic tube to model vascular occlusions caused by atherosclerosis and thrombosis.

Data Collection and Data Analysis

During an atherectomy and thrombectomy, the catheter-based device would be manually inserted into a blood vessel to drain or remove the blood clot or plaque (Heunis, Sikorski, & Misra, 2018). So, the procedures of this experiment attempted to simplify and replicate the genuine procedures. The purpose of these methods was to test the joint device's ability to remove plaque and blood clots in a mammalian blood vessel through in-vitro model testing. The procedure was timed to measure the general efficiency of the device to remove occlusions. This general method of testing a novel endovascular device in-vitro using models was influenced by a study by Chueh et al., which successfully and accurately tested numerous thrombectomy devices using occlusion and blood vessel models (2012).

In the proposed research, model thrombectomies were performed first. Prior to experimentation, the mass of the model blood clot placed inside the vessel was measured in grams using an electronic scale and written down in the corresponding row of the data table. The vacuum motor fan was then powered on and the blood clots were sucked from the blood vessel into the wet vacuum container. A back-and-forth motion was used to more accurately model a thrombectomy. The blood clots were not sucked through the PVC expandable repair coupling at the front of the device but directly by the plastic tubing that would connect the joint device and the plastic container. This had to be done to avoid clogging and damaging the ball bearings located inside the coupling. The experimenter attempted to get as much of the blood clot as possible and the time taken to do so was measured using a stopwatch. After the vacuum motor fan was powered off, the mass of the remaining blood clot present inside the blood vessel was measured in grams using an electronic scale. The model atherectomy was performed 5 times.

Next, model atherectomies were performed. Prior to experimentation, the mass of the

model plaque was measured in grams using an electronic scale. To perform the model atherectomy, the burr portion of the joint device was powered with 7.5 volts and moved back-and-forth through the model plaque, until a 5 cm diameter hole was made. The wet vacuum and balloon were not used together to observe the device's safety and ability to prevent the downstream flow of vascular debris. This was due to safety concerns caused by the powerful 120V vacuum motor fan. Because this was a proof of concept project, it was assumed that when negative pressure is applied to one end of the PVC pipe, the ground styrofoam pieces would be sucked into the vacuum container. The time taken to remove the plaque needed to create a 5 cm diameter hole was measured using a stopwatch. After the model atherectomy was completed, the mass of the remaining plaque was measured in grams using an electronic scale.

To make conclusions about the novel joint device, the average percentage of each type of occlusion removed and the average time taken to remove the occlusion were calculated using the data. For the model atherectomy, initial and post-procedure lumen diameter was also measured. The type of data collected was also influenced by the study by Chueh et al. (2012). While the study measured blood flow of the blood vessel before and after the endovascular procedure, the proposed research measured initial and post-procedure lumen diameter, which correlates with blood flow and does not require simulated blood flow in a model blood vessel. The joint device was considered successful if it increased the blood vessel lumen diameter. The purpose of this data was to prove that the joint atherectomy and thrombectomy device is capable of being inserted into a blood vessel to successfully remove plaque and blood clots.

Figure 9. <i>Experimental Design Diagram</i>
Title of the Experiment Exploring How to Merge an Aspiration Thrombectomy Device and a Rotational Atherectomy Device For Efficacious Individual or Joint Removal of Thrombi and Plaque Through In-Vitro Testing

General Research Goal

The research goal was to combine an aspiration thrombectomy device with a rotational atherectomy device for efficacious individual or joint removal of thrombi and plaque. The joint device should be able to clear a majority of the occlusions quickly because it combines two clinically successful devices for clearing vascular occlusions.

Engineering goals and benefits:

- Combine a rotational atherectomy device with an aspiration thrombectomy device.
 - Having one device able to perform both procedures simultaneously could make the overall procedure time shorter, decreasing the cost of the procedure.
 - Having one device that can perform both procedures means that the institution can save money training doctors and buying equipment.
- Engineering Challenge: Ensure that the rotational atherectomy device would not damage the delicate walls of the veins; ensure no vascular debris can flow downstream.
- Construct and test multiple designs and approaches to see which would most benefit the patient and medical institution.
 - This means observing which device removes the blood clots and plaque quickly and completely. This also means completing the procedure without causing any other complications (such as damaging blood vessel walls or causing occlusion pieces to travel downstream).
 - Ensure that the device does not allow large pieces of thrombi or plaque to flow downstream; this should prevent adverse events from occurring during a real procedure.

Measures of success:

The joint device should be able to increase the blood vessel lumen diameter by clearing the vascular debris. The time taken for the device to remove the occlusions was measured in seconds using a stopwatch. The occlusions removed were measured in grams using an electronic scale and the percentage removed from the model blood vessel was calculated as follows.

Percentage of occlusion removed = (mass of occlusion removed by device / initial mass of occlusion) x 100%

Because this engineering project was proof of the joint atherectomy and thrombectomy device concept, the device was considered successful if, on average, the lumen diameter increases.

Material Limitations:

- The model blood vessel was not an accurate model of a human blood vessel due to limited resources; instead, it only represented the shape of the blood vessel for in vitro testing of the joint device. The experimenter attempted to use comparable dimensions and a comparable shape. This limitation may affect the applicability of the joint device design.
- The model blood clot had a similar composition to blood clots found in human blood vessels but was not an exact representation of human blood clots. This was due to a lack of resources to precisely model the composition of thrombi. This limitation may negatively affect the validity of the joint device design.
- The model plaque had a similar composition to the plaque found in human blood vessels

but was not an exact representation of vascular plaque. This was due to a lack of resources to model its exact composition. This limitation may negatively affect the validity of the joint device design.

- Most rotational atherectomy devices have burrs that can rotate between 100,000 to 200,000 rotations per minute (rpm). Due to limited resources and safety concerns, the burr used in this experiment did not rotate at more than 1,000 rpm. This limitation may negatively affect the validity of the joint device design.

Current Approaches/Perspectives for Improving Catheter-Based Vascular Devices

- Improve the design of already existing atherectomy or thrombectomy devices.
 - This means changing the devices' mechanisms but preserving the functions they have performed in previous designs.
- Combine a currently available catheter-based device with pre-existing, catheter-based add-ons.
 - For example, in a study by Vo et al., the researchers tested the novel use of the GuideLiner catheter, an already existing type of catheter, to deliver rotational atherectomy burrs (2014).
- Improve atherectomy and thrombectomy procedural techniques.
 - For example, Yamamoto et al. tested a novel rotator technique, which incorporates pecking motions of a low speed followed by a high-speed rotational atherectomy (2019).
- Improve the general protocol for atherectomies and thrombectomies; this includes the steps from diagnosis to hospital discharge.
 - For example, Ascher et al. tested a fast-track procedure that can reduce the cost of the procedure and the number of adverse events that typically occur (2019).

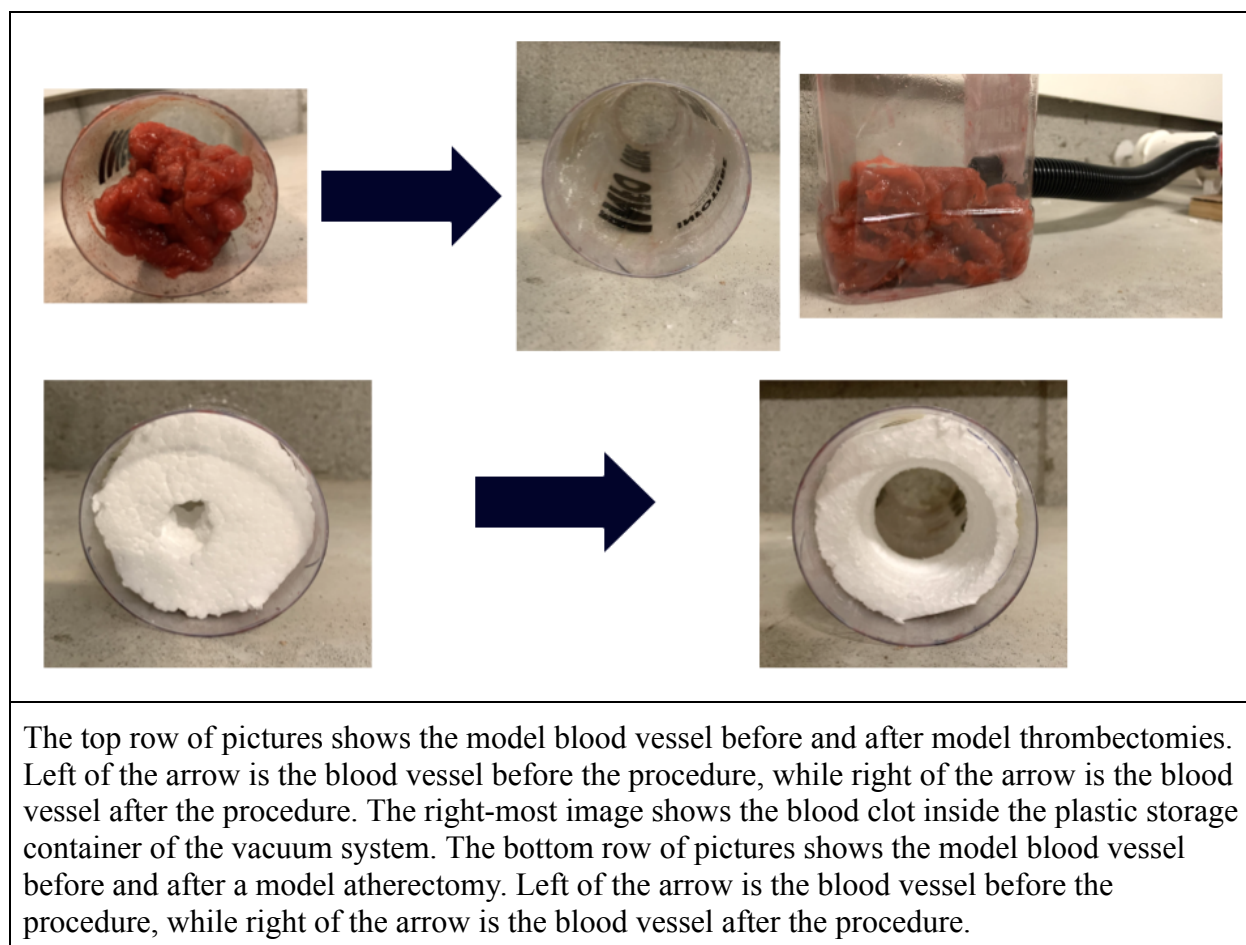
Experimenter's Approach/Perspective for Improving Catheter-Based Vascular Devices

Combining two pre-existing, catheter-based vascular devices to decrease the amount of time the procedure takes and to increase the percentage of occlusions removed.

Results

Pictures of the model blood vessel before and after the model thrombectomies and model atherectomies are shown in Figure 10.

Figure 10. Pictures of Model Blood Vessel After Model Thrombectomy and Model Atherectomy



As shown in Figure 10, it is visually clear the joint device increased the lumen diameter of the model blood vessel during both procedures. The model thrombectomy experimentation data are shown in Figure 11.

Figure 11. Experimentation Results Data Table

In-Vitro Testing Data Recording Table for Joint Atherectomy and Thrombectomy Device				
Model Thrombectomy				
Trial Number	Initial mass of blood clot (g)	Mass of blood clot removed (g)	Time taken to remove blood clot (s)	Percentage of blood clot removed (%)
1	204.10	204.10	5.34	100
2	230.90	230.90	3.24	100
3	190.80	190.80	6.32	100
4	211.70	211.70	5.35	100

5	195.80	195.80	2.88	100
Average:	206.66	206.66	4.63	100

As shown in Figure 11, on average, 100% of the blood clot was removed. The average time taken to remove the blood clot was 4.63 seconds. There is no variation between the 5 trials in the percentage of blood clots removed; there is some variation in the time taken to remove the blood clot. The longest trial lasted 6.32 seconds and the shortest trial lasted 2.88 seconds; this is a 3.44 second difference. The model atherectomy experimentation data are shown in Figure 12.

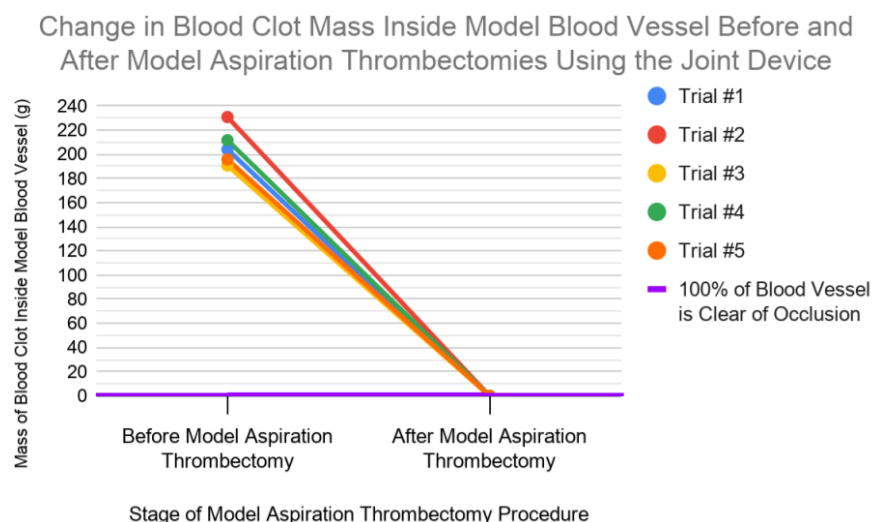
Figure 12. Experimentation Results Data Table

In-Vitro Testing Data Recording Table for Joint Atherectomy and Thrombectomy Device							
Model Atherectomy							
Trial #	Initial diameter of lumen (cm)	Post-procedure lumen diameter (cm)	Percentage lumen growth (%)	Initial mass of plaque (g)	Post-procedure mass of plaque (g)	Percentage plaque removed by mass (%)	Time taken for procedure (min: seconds: milliseconds)
1	1.50	5.30	353.33	1.86	1.05	43.55	01:16:27
2	1.50	5.00	333.33	1.69	1.07	36.69	01:20:77
3	1.50	5.50	366.67	1.91	1.20	37.17	01:41:26
4	1.50	5.20	346.67	1.67	1.00	40.12	01:15:97
5	1.50	5.00	333.33	1.70	1.04	38.82	01:13:85
Average	1.50	5.20	346.67	1.77	1.07	39.27	01:22:02

As shown in Figure 12, on average, the 1.5 cm lumen diameter increased by 346.67%. In other words, it increased from 1.50 cm to 5.20 cm. On average, 39.27% of plaque was removed from the initial mass of plaque in the blood vessel. The average time taken to perform the model atherectomy was 1 minute, 22 seconds, and 2 milliseconds. There is very little variation in the percentage lumen growth data, percentage plaque removed by mass data, and time taken for procedure data. Figure 13 shows a line graph of the change in blood clot mass before and after

aspiration thrombectomies were performed using the joint device.

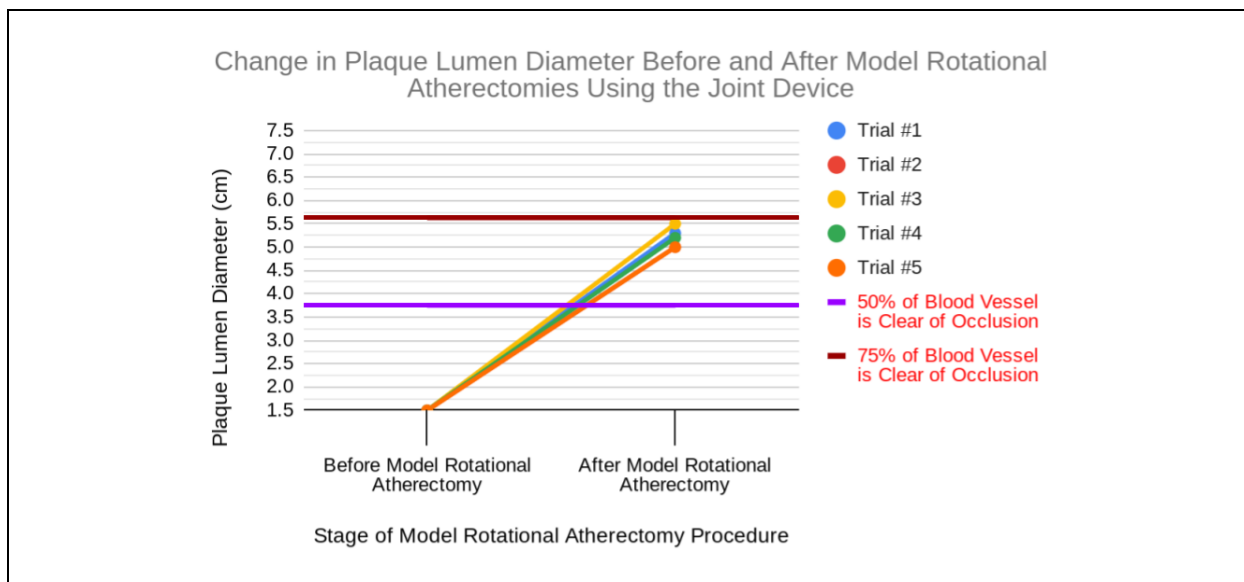
Figure 13. Line Graph of Change in Blood Clot Mass Before and After Model Aspiration Thrombectomies Performed Using Joint Device



This line graph depicts the change in blood clot mass before and after model aspiration thrombectomies were performed using the joint device. The purple line at the bottom of the line graph indicates the point at which 100% of the blood vessel is clear of occlusions.

As shown in Figure 13, the mass of the blood clot inside the model blood vessel decreased, on average, from approximately 206.66 grams to 0.00 grams. As indicated by the violet horizontal line, this means that 100% of the blood vessel was clear of occlusions in all 5 trials. Figure 14 shows a line graph of change in plaque lumen diameter before and after model rotational atherectomies were performed using the joint device.

Figure 14. Line Graph of Change in Plaque Lumen Diameter Before and After Model Rotational Atherectomies Performed Using the Joint Device



This line graph depicts the change in plaque lumen diameter before and after model rotational atherectomies performed using the joint device. The burgundy horizontal line depicts the point at which 75% of the blood vessel would be clear of occlusions. The violet horizontal line depicts the point at which 50% of the blood vessel was clear of occlusions.

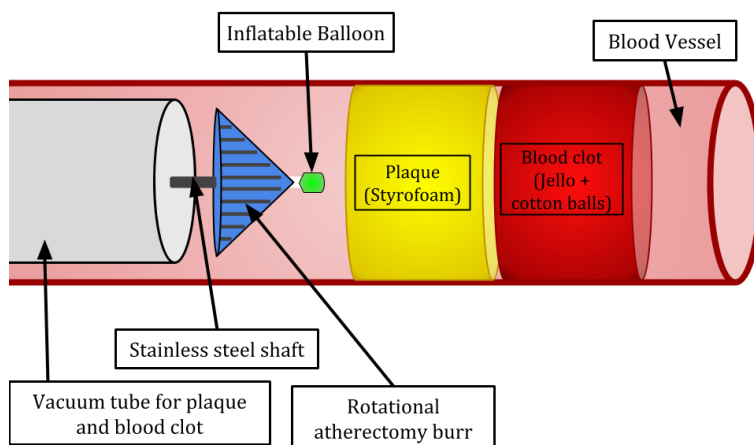
As shown in Figure 14, the plaque lumen diameter increased in all 5 trials by the end of the model rotational atherectomy procedure. As depicted by the violet horizontal line, all 5 trials cleared enough plaque for 50% of the blood vessel to be clear of occlusions. As depicted by the burgundy horizontal line, none of the trials cleared 75% of the blood vessel.

Discussion

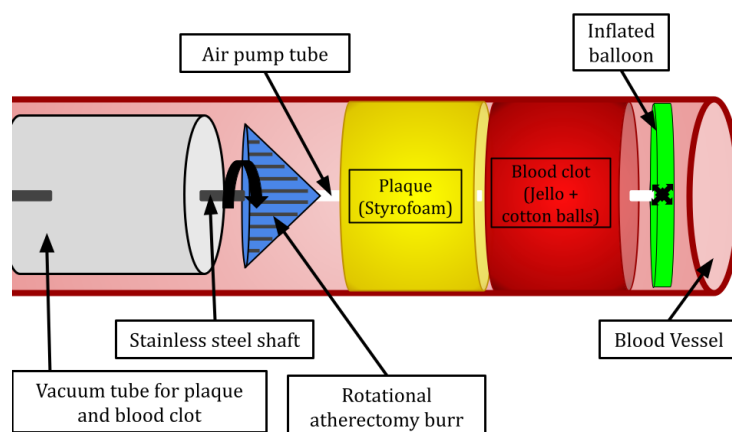
The purpose of this experiment was to improve on already existing atherectomy and thrombectomy device technology by producing a device that can conduct an atherectomy or thrombectomy independently and simultaneously. The overall goal of this research was to design, construct, and test an efficacious, efficient, and safe joint rotational atherectomy and aspiration thrombectomy device. Figure 15 contains a storyboard of what the device does conceptually to remove blood clots and plaque simultaneously.

Figure 15. Concept Diagram of Joint Thrombectomy and Atherectomy Device in Use to Clear Both Types of Occlusions Simultaneously

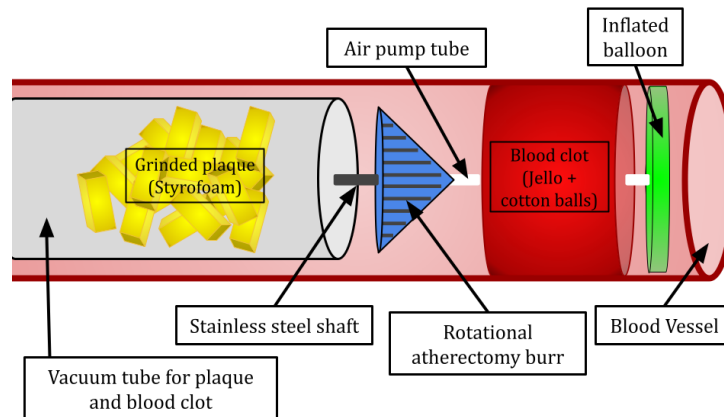
Part 1. The joint device is inserted into a human blood vessel and positioned directly in front of the occlusions.



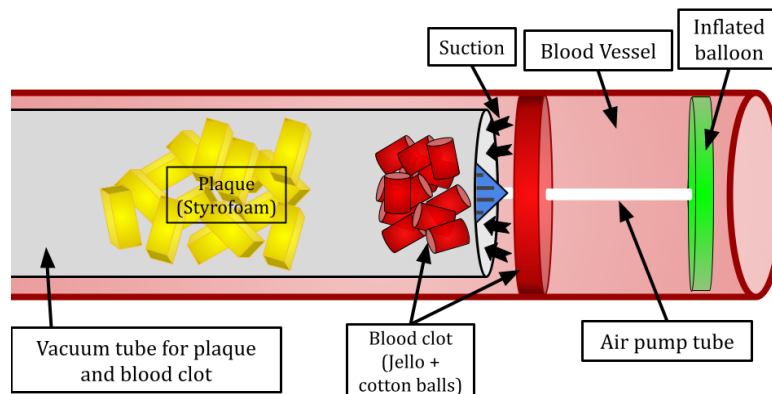
Part 2. The inflatable balloon is pushed forward, through the plaque and blood clot until it is on the other side of the occlusions. The balloon is inflated until blood flow is blocked. The high-speed rotating burr is powered on.



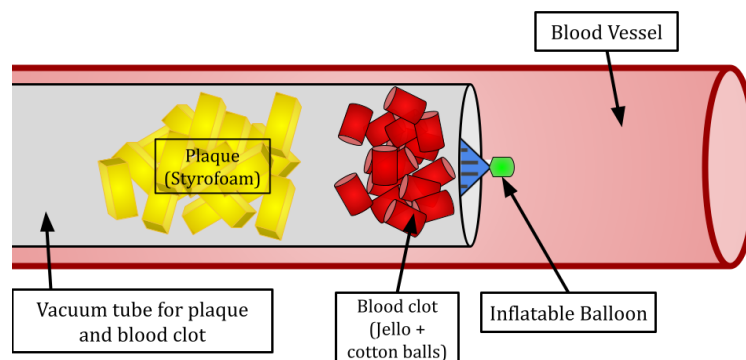
Part 3. The rotating burr cuts through the plaque and the vacuum motor fan generates negative pressure that allows for the plaque to be captured. The high-speed rotating burr is stopped and the inflated balloon is inflated once again to ensure that the blood flow in the blood vessel is still blocked.



Part 4. The rotating burr is tucked into the main tube, and the vacuum motor fan is powered once again to suction the blood clot. The balloon remains inflated to temporarily halt blood flow.



Part 5. Once all of the vascular debris has been suctioned by the joint device, the balloon is deflated and retracted back to the burr. The blood vessel has been cleared of occlusions and the joint device can be removed from the blood vessel.



According to the results, the joint device increased the lumen diameter of blood vessels

with blood clots or plaque. The mass of the blood clot present inside the model blood vessel decreased, on average, from approximately 206.66 grams to 0.00 grams. This means that 100% of the blood vessel was cleared of occlusions in all the trials. The plaque lumen diameter increased in all 5 trials by the end of the model rotational atherectomy procedure. All 5 trials resulted in 50% of the blood vessel being cleared of plaque. On average, the 1.5 cm lumen diameter increased by 346.67% to 5.20 cm. Furthermore, the percentage plaque removed by mass was 39.27% from the initial mass of the plaque. These results indicate that the joint atherectomy and thrombectomy device can successfully increase the lumen diameter size of an occluded blood vessel.

The efficiency of the joint device was measured using time data. The average time taken to remove the blood clot using the joint device was 4.63 seconds. The longest trial lasted 6.32 seconds and the shortest trial lasted 2.88 seconds. The average time taken to perform the model atherectomy was 1 minute, 22 seconds, and 2 milliseconds. These average times could not be compared with other studies because the in-vitro procedures of this experiment are unique and have not been replicated by others. As a result, the efficiency of the joint device was not compared with already existing devices and the relative efficiency of the device was not determined. It may be possible to determine relative efficiency in the future by following the same procedures of another study.

It was proposed that the device would be safe by preventing the downstream flow of vascular occlusions through the use of a balloon. This safety feature could not be quantitatively tested during the experiment due to safety concerns caused by the powerful 120v vacuum motor fan and vacuum container. However, conceptually, the joint device should be able to prevent the downstream flow of vascular occlusions, because on either side of the occlusion would be a

vacuum and balloon. In brief, quantitative data showed that the designed and constructed device is efficacious in clearing vascular occlusions; however, the safety features were not quantitatively tested and the device's relative efficiency could not be determined. So, the engineering goals and suspected outcomes were partially achieved. Due to the limitations, much more work has to be done to further improve and test the device.

In the future, an expanding burr should be incorporated into the joint device so that the vacuum can follow the burr through the blood vessel. This would further prevent the downstream flow of vascular debris and increase the safety of the device. In the current design, the cone burr diameter was limited by the vacuum pipe diameter. Also, a much stronger balloon, similar to what is used during a balloon angioplasty, should be incorporated into the device. This would make the research and device more applicable and realistic. The rotating burr should be able to rotate 4000 rotations per minute, similar to that of a modern rotational atherectomy device. This could be done using compressed air to rotate the shaft and would also make the joint device prototype more applicable. This improvement would also allow for the joint device to be tested on harder, more realistic plaque models. These features could not be incorporated into the device because the resources were not available during the time of experimentation. In the future, the vacuum system and vascular debris capture system need to be improved so that the safety of the joint device can be quantitatively measured and compared to similar devices. This might involve using stronger materials for the construction of the device. Finally, the device should be tested against model plaque and a blood clot at the same time to further test the device's applicability in a medical institution; this was avoided during the proposed experiment due to the ball bearings in the device, which easily got clogged. An alternative for ball-bearings should be researched and used.

A possible source of uncertainty was inaccuracies in measuring the lengths of the procedures. It was difficult to start and stop the stopwatch during the corresponding procedure start and end times. This source of uncertainty directly affects the efficiency data collected during experimentation. However, because the length of the procedures could not be compared to other studies and therefore was not used to make conclusions, this source of uncertainty does not affect the conclusions of the research. To fix this error in the future, when relative efficiency is relevant, a mechanical timer can be connected to the power buttons of the joint device, so that the start and end times of the procedure can be accurately measured.

Regardless of the limitations, the proposed research suggests that combining more than one successful endovascular device may lead to a more safe and efficacious device. Combining existing catheter-based technologies may be a viable path for developing a gold standard device for clearing endovascular occlusions. With further development and testing, the proposed joint device can be applicable in medical institutions to conduct atherectomies and thrombectomies. It can benefit the patient by reducing the number of surgical interventions by being a 2 in 1 device, possibly shortening procedure time, and increasing the success rate of the procedure. The device can benefit medical institutions by reducing material cost, procedure time, and medical professional training cost since one device can be used for two procedures. The novel joint device addresses and improves on almost all aspects of currently used devices.

References

- Ascher, E., Chait, J., Pavalonis, A., Marks, N., Hingorani, A., & Kibrik, P. (2019). Fast-track thrombolysis protocol: A single-session approach for acute iliofemoral deep venous thrombosis. *Journal of Vascular Surgery: Venous and Lymphatic Disorders*, 7(6), 773-780. doi:10.1016/j.jvsv.2019.06.018
- Behrens, G., & Bjarnason, H. (2015). Venous Thromboembolic Disease: The Use of the Aspiration Thrombectomy Device AngioVac. *Seminars in Interventional Radiology*, 32(4), 374-378. doi:10.1055/s-0035-1564792
- Bentzon, J., Otsuka, F., Virmani, R., & Falk, E. (2014). Mechanisms of Plaque Formation and Rupture. *Circulation Research*, 114(12), 1852-1866. doi:https://doi.org/10.1161/CIRCRESAHA.114.302721
- Bhat, T. M., Afari, M. E., & Garcia, L. A. (2017). Atherectomy in Peripheral Artery Disease: A Review. *Journal of Invasive Cardiology*, 29(4), 135-144. Retrieved September 7, 2020, from invasivecardiology.com/articles/atherectomy-peripheral-artery-disease-review
- Chernysh, I. N., Nagaswami, C., Kosolapova, S., Peshkova, A. D., Cuker, A., Cines, D. B., . . . Wesel, J. W. (2020). The distinctive structure and composition of arterial and venous thrombi and pulmonary emboli. *Nature-Scientific Reports*, 10(1), 1-12. Retrieved September 7, 2020, from <https://doi.org/10.1038/s41598-020-59526-x>
- Chueh, J. Y., Wakhloo, A. K., & Gounis, M. J. (2012). Effectiveness of Mechanical Endovascular Thrombectomy in a Model System of Cerebrovascular Occlusion. *American Journal of Neuroradiology*, 33(10), 1998-2003. doi:10.3174/ajnr.a3103
- Davaine, J., Quillard, T., Chatelais, M., Guilbaud, F., Brion, R., Guyomarch, B., . . . Gouëffic, Y. (2016). Bone Like Arterial Calcification in Femoral Atherosclerotic Lesions: Prevalence

- and Role of Osteoprotegerin and Pericytes. *European Journal of Vascular and Endovascular Surgery*, 51(2), 259-267. doi:10.1016/j.ejvs.2015.10.004
- Gepstein, L., Hayam, G., & Ben-Haim, S. A. (1997). A Novel Method for Nonfluoroscopic Catheter-Based Electroanatomical Mapping of the Heart. *Circulation*, 95(6), 1611–1622. <https://doi.org/10.1161/01.cir.95.6.1611>
- Heunis, C., Sikorski, J., & Misra, S. (2018). Flexible Instruments for Endovascular Interventions: Improved Magnetic Steering, Actuation, and Image-Guided Surgical Instruments. *IEEE Robotics & Automation Magazine*, 25(3), 71-82. doi:10.1109/mra.2017.2787784
- Pahwa, R., & Jialal, I. (2010). *Atherosclerosis*. StatPearls Publishing. Retrieved January 06, 2021, from <https://www.ncbi.nlm.nih.gov/books/NBK507799/>.
- Przybyłowski, C. J. (2014). Evolution of endovascular mechanical thrombectomy for acute ischemic stroke. *World Journal of Clinical Cases*, 2(11), 614–622. <https://doi.org/10.12998/wjcc.v2.i11.614>
- Reisman, M., Harms, PhD, V., Whitlow, P., Feldman, T., Fortuna, R., & Buchbinder, M. (1997). Comparison of Early and Recent Results With Rotational Atherectomy. *Journal of the American College of Cardiology*, 29(2), 353–357. [https://doi.org/10.1016/s0735-1097\(96\)00478-0](https://doi.org/10.1016/s0735-1097(96)00478-0)
- Ritchie, J. L., Hansen, D. D., Vracko, R., & Auth, D. C. (1986). Mechanical thrombolysis: A new rotational catheter approach for acute thrombi. *Circulation*, 73(5), 1006-1012. doi:10.1161/01.cir.73.5.1006
- Spiotta, A. M., Chaudry, M. I., Hui, F. K., Turner, R. D., Kellogg, R. T., & Turk, A. S. (2014). Evolution of thrombectomy approaches and devices for acute stroke: A technical review. *Journal of NeuroInterventional Surgery*, 7(1), 2-7. doi:10.1136/neurintsurg-2013-011022

- Steele, P. M., Chesebro, J. H., Stanson, A. W., Holmes, D. R., Dewanjee, M. K., Badimon, L., & Fuster, V. (1985). Balloon angioplasty. Natural history of the pathophysiological response to injury in a pig model. *Circulation Research*, 57(1), 105-112.
doi:10.1161/01.res.57.1.105
- Thrombosis. (n.d.). Retrieved January 06, 2021, from <https://www.worldthrombosisday.org/issue/thrombosis/>
- Tocantins, L. M. (1935). Platelets And The Structure And Physical Properties Of Blood Clots. *American Journal of Physiology-Legacy Content*, 114(3), 709-715.
doi:10.1152/ajplegacy.1936.114.3.709
- Vo, M., Minhas, K., Kass, M., & Ravandi, A. (2014). Novel use of the GuideLiner catheter to deliver rotational atherectomy burrs in tortuous vessels. *Case Reports in Cardiology*, 2014, 1-5. doi:10.1155/2014/594396
- Yamamoto, T., Yada, S., Matsuda, Y., Otani, H., Yoshikawa, S., Sasaoka, T., . . . Ashikaga, T. (2019). A Novel Rotablator Technique (Low-Speed following High-Speed Rotational Atherectomy) Can Achieve Larger Lumen Gain: Evaluation Using Optimal Frequency Domain Imaging. *Journal of Interventional Cardiology*, 2019, 1-7.
doi:10.1155/2019/9282876

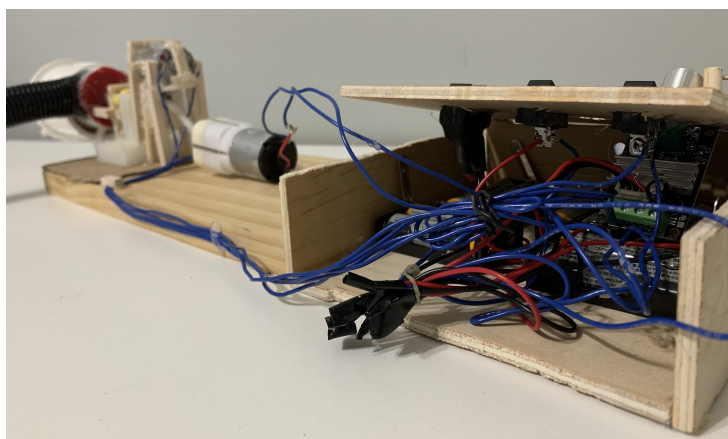
Appendix A

Figure A1

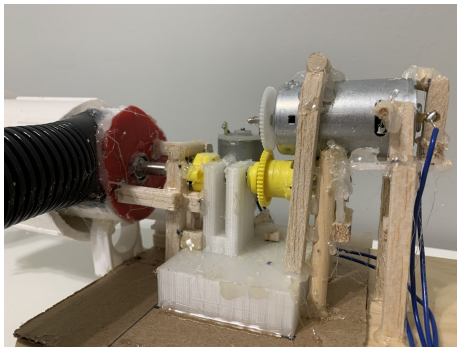
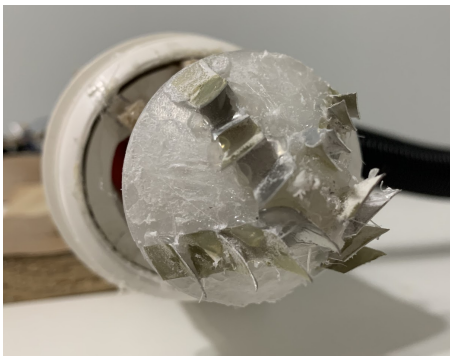
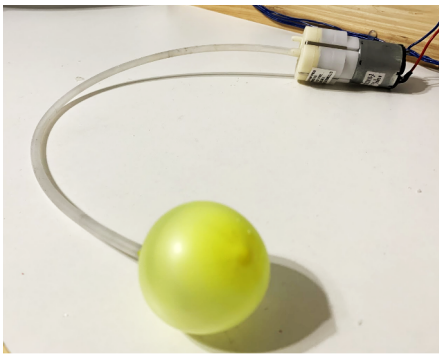
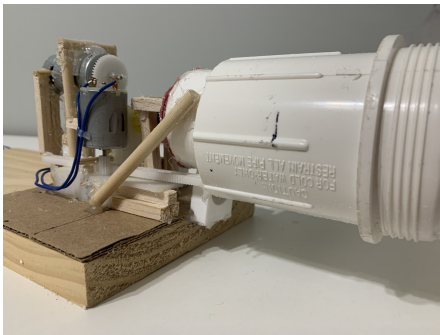
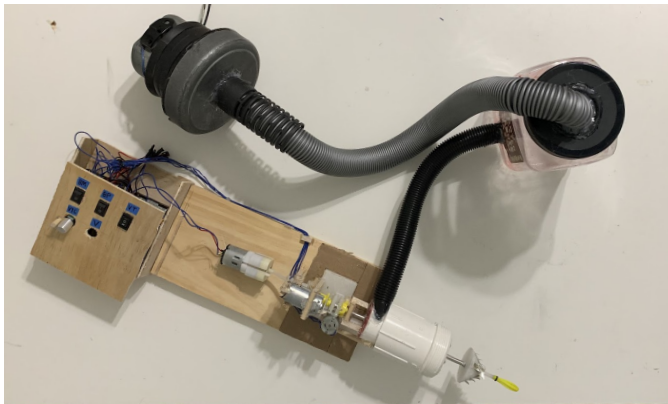


Switches
 BM - Burr Motor (On/Off)
 BP - Balloon (On/Off)
 VT - Vacuum Tube Movement (On/Off)
 VTC - Vacuum Tube Speed Control(Slow/Fast)
 V - Vacuum (On/Off)

Figure A2



Appendix A shows the wiring and switchboard for the joint atherectomy and thrombectomy device. Figure A1 shows the labeled switchboard. On the right is a key for each of the switches. Figure A2 shows the wiring and batteries under the switchboard. All of the electrical wiring was done using 22 gauge silicone electric wire, tin-lead rosin core solder wire, and a soldering iron.

Appendix B	
Figure B1	Figure B2
	
Figure B3	Figure B4
	
Figure B5	Figure B6
	
Appendix B contains pictures of each component of the joint thrombectomy and atherectomy device. Figure B1 is an image of the thrombectomy vacuum system. Figure B2 is an image of the rotational atherectomy system. Figure B3 is an image of the rotating burr. Figure B4 is an image of the balloon component. Figure B5 is an image of the sliding vacuum tube. Figure B6 is an image of all the components connected.	