Hemocompatible Tunable Blood Shunt for Norwood Recipients with Single Ventricle Physiology

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A. Abstract

Hypoplastic Left Heart Syndrome is a congenital heart defect characterized by an underdeveloped left side of the heart. The current practice is staged palliation beginning with the Norwood Procedure, which has a high morbidity rate and constitutes a minimum of 30% of revision surgeries. Norwood procedure is performed within days after birth, redirecting blood between the pulmonary and systemic circulation with a Blalock-Taussig Shunt. The fixed geometry of the shunt doesn’t account for flow ratio changes with patient growth, limiting oxygen delivered to the tissues as the infant grows, leading to death. A new geometrically tunable hydrogel-based blood shunt addresses the limitations of a static shunt by adjusting geometry in proportion to the patient’s growth. Increasing the degree of crosslinking in a hydrogel-coated inner lumen of a shunt causes swelling to decrease, thus increasing lumen diameter, thereby modulating blood flow. This was accomplished through a methacrylated dextran hydrogel crosslinked via photoexcitation of LAP, a near-UV photoinitiator; both are known to be hemocompatible. The design was assessed for hemocompatibility and functionality in vitro using ASTM F756-17, ASTM F619, and MATLAB image analysis. The first prototype achieved the correct lumen diameter increase in 5 minutes of near-UV exposure. Hemolysis testing on the hydrogel lumen yielded a nonhemolytic score by ASTM F756-17 for both extract and direct contact testing. By accounting for the changing blood flow in a growing patient with this novel geometrically tunable shunt design, the patient outcome will improve and will mitigate the risk of having to undergo another invasive open-heart procedure.

B. Clinical Need

Infants can be born with a broad range of congenital cardiovascular defects that result in single ventricle physiology, causing respiratory distress from the inadequate systemic blood oxygenation resulting in cardiogenic shock if surgical intervention is not performed immediately. The incidence of these defects is approximately 1 per 5,000 births [1]. Heart transplantation is very limited due to low neonatal donor availability. Surgical advancements have increased the survival rate using staged palliation with the Norwood- Glenn- Fontan procedures. The Norwood procedure is completed within the first few days after birth and involves implanting a systemic-pulmonary blood shunt to connect the single functional ventricle to both circulations. The single ventricle can then drive blood to both the body and lungs concurrently. The shunt implemented in the Norwood will remain in use until the second procedure which is performed at when the patient is roughly 6 months old [2]. Mortality rates of the Norwood procedure are the highest among congenital heart surgeries and pose an ongoing challenge for the infants [3].

Following the Norwood procedure, patients are at risk of serious complications stemming from instabilities in blood oxygenation leading to death. Instabilities in the blood oxygenation can result from the diameter of the shunt relative to the body size of the patient. A shunt that is too narrow in diameter has an increased internal resistance, which may lead to pulmonary hypoperfusion, higher shear stresses, and irregular blood flow patterns that can lead to hemolysis and thrombosis. A shunt that is too large in diameter has a lower internal resistance, which draws more blood volume to the lungs and away from the systemic circulation, negatively impacting the oxygenation of to the lungs and away from the systemic circulation. This causes tissues to not receive adequate oxygenation. Therefore, the shunt must be of an appropriate diameter to facilitate the health of the patient.

Currently, a commercially available, fixed diameter shunt is utilized by surgeons in the Norwood procedure, as shown in Figure 1. The most widely used is the GoreTex Propaten Vascular Graft configured for pediatrics shunt, which is a modified Blalock-Taussig shunt. It is comprised of an expanded polytetrafluoroethylene (ePTFE) tube that is lined with a covalently bound bioactive heparin to minimize
thrombogenicity $^{[4]}$. However, the changes in vessel growth, cardiac output, and pulmonary vascular resistance as the patient grows will alter the blood oxygenation balance. By utilizing a fixed diameter design in the treatment of these patients, the patients are more likely to develop secondary complications as mentioned above. Norwood revision procedures are performed due to incompatibility with patient geometry, currently occurring in 30% of the 1,000 procedures done annually in the US.

The solution to this problem was based on proof of concept work performed by a previous senior design group for this device. The previous design team showed design feasibility of a lumen-expanding shunt device through computational modeling and prototype verification with gelatin hydrogel and glutaraldehyde crosslinking as the biomaterials. The focus of this design is to improve the hemocompatibility of the design by utilizing novel materials while retaining the widening lumen parameters set forth $^{[5]}$.

C. Project Objective

The objective of this design is to address the limitations of the fixed diameter shunt by designing a modified Blalock-Taussig shunt with a tunable inner diameter that widens to accommodate patient growth and is hemocompatible. The photocrosslinking capabilities of a methacrylated hydrogel in the presence of a small molecule photoinitiator were utilized to increase the inner diameter of the shunt. When exposed to near UV light, around 400nm, the small molecule photoinitiator Lithium phenyl-2,4,6-trimethylbenzoylphosphinate (LAP), initiates a free radical reaction between the methacrylate groups on the hydrogel polymer chain, crosslinking the chains together and increasing the inner lumen diameter. Near-UV light is not cytotoxic, therefore it will not adversely affect the tissues surrounding the shunt $^{[7]}$. Dextran was used as the polymer material in this approach, as it possesses the hemocompatible and cytocompatible traits required for this indication and can be methacrylated through different techniques $^{[6]}$.

D. Design Solution

Inputs

To accommodate patient growth, the shunt must increase in inner diameter by 15-18% while changing less than 1% in outer diameter, depicted in Figure 2. The values for the inner diameter increase were determined by a previous senior design team who modeled patient growth relative to pulmonary flow as a power-law equation based on available patient data. They determined the relevant flow needed to sustain the patient over time, which then was extrapolated to the relevant diameter needed based on Hagen-Poiseuille flow through a pipe. They determined that the 15-18% change in diameter was optimal for maintaining an adequate flow ratio if the outer diameter remained fixed, as it would in normal human physiology $^{[5]}$. The inner lining must not separate from the rigid outer layer, as this could cause a major clot in the bloodstream of the patient and could potentially be fatal if the detached lining were to obstruct an artery. This was assessed by visual inspection.
during device fabrication. The inner lining of the design must pass material-induced hemolysis testing based on ASTM F756-17: Standard Practice for Assessment of Hemolytic Properties of Materials. The material lining must be nonhemolytic, or exhibit a hemolytic index of 0-2 above the negative control, low density polyethylene, when testing for material-induced hemolysis conditions for hemocompatibility.

**Overview and Fabrication**

The first step in manufacturing the hydrogel for this project is adding the methacrylate functional groups to the polymer. A ring-opening mechanism of the dextran backbone and subsequent methacrylation by glycidyl methacrylate was used to functionalize the polymer, as seen in Figure 3. By adjusting the ratio of dextran to methacrylate groups added in these reactions, the degree of functionalization can be controlled. Previous studies have shown that 11% methacrylation will prevent equilibrium swelling of the hydrogel [6]. This will allow the gel to maintain the original lumen diameter after being exposed to an aqueous environment. By increasing the duration of near UV exposure, the DexMA inner layer will increase in lumen diameter while the outer diameter will remain unchanged. Ideally, the DexMA inner layer would be covalently bound to an ePTFE outer layer in the final product. However, we were unable to acquire ePTFE tubing due to resource limitations, so functionalized polymethyl methacrylate (PMMA) served as the outer layer instead to demonstrate feasibility.

To determine what degree of crosslinking would be necessary to accomplish the necessary change in diameter, three different degrees of functionalized of DexMA were prepared: 10% DexMA, 50% DexMA, and 95% DexMA. Three 10% (w/v) hydrogels of each subsequent group were cast and swollen to equilibrium in PBS. They were then subjected to photocrosslinking experimentation to quantify the overall change in volume upon 10 minutes of UV-exposure and change in diameter throughout the ten minutes in one-minute intervals. MATLAB image analysis was used to quantify the change in diameter, and see if the rate of diameter change was influenced by the % functionalization of the samples. The overall volumetric change was quantified by digital caliper; measuring pre- and post-crosslinking hydrogel height and diameter.

To translate the solid cylinder geometry that was tested to a hollow cylinder geometry of the prototype, the theoretical volumetric decrease was calculated for a shunt with the dimensions 10mm (length) x 8mm (outer diameter) x 3.5mm (inner diameter) relative to one with both a 15% and an 18% larger inner diameter, using Equation 1. The dimensions are based on the prototype final size. It was calculated that a change of 7.63% to 9.29% in volume would correspond to the desired inner diameter change. If the hydrogels created can achieve this change in volume in 10 minutes or less of UV exposure, then they should theoretically provide the desired 15-18% expansion needed by the patient. Additionally, the hydrogel exhibiting the fastest change in diameter would also be preferable for this indication, as it would minimize the amount of time needed to achieve the diameter expansion needed.

A significant decrease in volume upon UV-crosslinking of each of the functionalized gels was observed in the crosslinking experiment. As seen in Figure 4A, the volumetric decrease was 14.8% for the 10% methacrylated DexMA, 22.1% for the 50% methacrylated DexMA, and 30.5% for the 95% methacrylated DexMA, all of which are statistically significant by paired two-tailed T-test assuming equal variances (p < 0.001). Figure 4B showed that increasing methacrylation content does not drastically increase the rate at which the crosslinking occurs. There was not a significant difference between the slopes of the lines, but the y-intercepts of the lines were significantly different (i.e. post-swelling hydrogel diameter) between each condition. On average, the 10% DexMA decreases in diameter by 0.07 mm/minute, 50% DexMA decreases 0.08 mm/minute, and 95% DexMA decreases 0.1 mm/minute.

Based on the results of this experiment and theoretical considerations, 95% DexMA was optimal for this indication. It exhibited a large decrease in volume upon UV-crosslinking for 10 minutes; far in excess of the

\[ V = \pi \times (R^2 - r^2) \times L \] (Eq. 1)
needed 7.63% to 9.29%, therefore needing the least amount of time to achieve the requirement of 15-18% inner diameter expansion. This material was selected to proceed with all fabrication and further verification testing.

95% DexMA was bound to a functionalized PMMA tube using methodology portrayed in Figure 5A. Unmodified PMMA will underwent plasma treatment for 1-minute using a PDC-32G Plasma Cleaner, thus oxidizing it and making the surface reactive. The reactive PMMA was immediately submerged in excess methacrylic anhydride for 10 minutes to introduce free methacrylates to the surface of the PMMA tubing. The methacrylated PMMA was filled with 95% DexMA and LAP solution (10%; 0.25% w/v) and photocrosslinked for 3.5 minutes to cause the hydrogel to form and covalently bind to the PMMA. The center was then extracted using a 3.5mm biopsy punch, and the device was swelled in PBS to equilibrium for 24 hours. The 15-18% inner diameter expansion was achieved upon a second photoinitiation event. A preliminary prototype was fabricated as seen in Figure 5B.

![Figure 4](image1.png)

**Figure 4.** A: Volume comparison - 10 minutes of UV-crosslinking of DexMA gels (n = 3 per group; ± stdev; p < 0.001). B: Diameter change upon UV-crosslinking of DexMA gels based on image capture analysis in MATLAB (± stdev).

![Figure 5](image2.png)

**Figure 5.** A. Schematic of the PMMA tubing functionalization process and prototype fabrication. B. A top and side view of our preliminary prototype, consisting of a rigid PMMA outer layer filled with 95% DexMA hydrogel with 3.5mm extracted from the center.

**Intended Use**

The embedded LAP would promote crosslinking *in vivo* when a physician applies a near UV light source arthroscopically to the site of the shunt when the diameter of the tube would need to be increased to accommodate for patient growth [7]. A LAP-eluting catheter with a hollow fiber optic light would be inserted into patient arthroscopically and maneuvered to be inside of the shunt. Once inside of the shunt, LAP would diffuse into the hydrogel lumen. Upon near UV exposure from the fiber optic light, photocrosslinking activity occurs. The lumen inner diameter is expanded due to hydrogel contraction from photocrosslinking.

**E. Verification Testing**

To prove that the photoinitiation mechanism would be applicable to this proposed design with hemocompatible materials, verification testing was performed. The prototype in Figure 5B was tested for the ability to achieve 15-18% lumen expansion while retaining the outer diameter. This was performed using image
processing in MATLAB in lieu of any relevant engineering standards. To test the connection of the hydrogel with the PMMA tube, physical inspection was employed, also in lieu of any relevant engineering standards. To assess hemolysis of the hydrogel coating, hemolysis testing was performed according to ASTM Standard F756 - 17: Standard Practice for Assessment of Hemolytic Properties of Materials, as it details quantitative metrics for determining biochemical hemolysis tendencies of designs. For this criterion, both the direct contact submergence test and the extract test were performed, determining if there was hemolytic material in the device which would adversely impact the viability of the red blood cells and harm the patient. Extract testing was in compliance with ASTM Standard F619: Standard Practice for Extraction of Medical Plastics.

Methods

For contraction testing, a handheld UV light (3D Printer UV Resin Curing Light, 405nm, 6W output) was used to induce DexMA crosslinking in presence of LAP in the prototype (Figure 5B). The degree of crosslinking that occurred during near UV exposure and respective contraction was quantitatively assessed by processing images taken prior to and after exposure using MATLAB, incorporating aspects of ASTM F2603: Standard Guide for Assessing Images of Polymeric Tissue Scaffolds. The outer diameter could not change more than 1%; quantitatively assessed in the same manner. A plot of both inner and outer diameter change over time was generated and a linear regression was fit to each set of data. Given that only one sample was able to be tested, no statistics were performed.

The material induced hemolysis of 95% DexMA was tested according to ASTM F756-17: Standard Practice for Assessment of Hemolytic Properties of Materials. Material extracts were prepared as specified in ASTM F619: Practice for Extraction of Medical Plastics. Relative to a positive (Buna-N-Rubber) and negative (Low Density Polyethylene) control plastic material, the hemolytic activity of 95% DexMA (10% w/v) hydrogels was assessed and reported as specified.

Standards

An integral part of the design process for this new blood shunt is the study and use of ASTM International standards. These standards were employed to inform the design requirements and specifications of this new pediatric blood shunt. This enabled us to consider not only the engineering design but the translational attributes for success in latter development stages. Table 1 identifies 10 critically important ASTM standards that were incorporated into the design, fabrication and testing of this device.

### Table 1. List of Relevant ASTM Standards

<table>
<thead>
<tr>
<th>ASTM Standard</th>
<th>Inform Design of New Blood Shunt</th>
<th>Implementation</th>
</tr>
</thead>
<tbody>
<tr>
<td>ASTM F2900-11: Standard Guide for Characterization of Hydrogels used in Regenerative Medicine</td>
<td>Provides methods to assess hydrogel biological properties, kinetics of formation, degradation and agent release, physical and chemical stability and mass transport capabilities.</td>
<td>Portions of this standard were used to design a study to determine the LAP diffusion profile into the DexMA hydrogel, but ultimately the study was not carried out due to the COVID-19 outbreak.</td>
</tr>
<tr>
<td>ASTM F2450-18: Standard Guide for Assessing Microstructure of Polymeric Scaffolds for Use in Tissue-Engineered Medical Products</td>
<td>The porosity of the hydrogel directly impacts its bioactivity or bioinert properties, which can be effectively assessed using this standard.</td>
<td>After further review of this standard, it was not as relevant to our design objective in assessing hemocompatibility of this design and was not implemented.</td>
</tr>
<tr>
<td>ASTM F2603: Standard Guide for Interpreting Images of Polymeric Tissue Scaffolds</td>
<td>To ensure that the design contracts an appropriate amount, proper image processing and interpretation must be completed using the guide set forth in this standard.</td>
<td>Portions of this standard were used to design the MATLAB image analysis code that was utilized to interpret hydrogel images.</td>
</tr>
<tr>
<td>ASTM F756-17: Standard Practice for Assessment of Hemolytic Properties of Materials</td>
<td>To ensure that the hydrogel material does not cause hemolysis by biochemical mechanisms, this standard will be employed in the design of submergence tests for thrombogenicity.</td>
<td>This standard was used directly in conjunction with ASTM F619-14 (Practice for Extraction of Medical Plastics) to test our prototype for hemocompatibility relative to industry standard positive and negative control biomaterials.</td>
</tr>
<tr>
<td>ASTM F2382-18: Standard Test Method for Assessment of Circulating Blood-Contacting Medical Device Materials on</td>
<td>As part of the hemocompatibility testing, the partial thromboplastin time (PTT) must be determined to ensure that the device will not cause coagulation in vivo.</td>
<td>This standard was going to be assessed as part of the hemocompatibility requirement but was unable to be performed due to the</td>
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</table>
Partial Thromboplastin Time (PTT) shortened verification testing time as a result of the COVID-19 outbreak.

**ASTM 2150-17 (6, 7, and 8):** Standard Guide for Characterization and Testing of Biomaterial Scaffolds Used in Tissue-Engineered Medical Products  
Testing the chemical, physical, and mechanical properties of the entire device, including the fixed outer sheath, would also be applicable to ensuring design success.  
A future design team could use this standard to assess the chemical, physical and mechanical properties of the prototype to ensure that it would function as needed in this indication.

**ASTM F2027-16:** Standard Guide for Characterization and Testing of Raw or Starting Materials for Tissue-Engineered Medical Products  
Ensuring that the materials that are used in the design are of sufficient purity and have appropriate chemical, physical and mechanical properties is imperative to the safety of patients and must be performed prior to in vivo testing.  
This standard is applicable to future design teams who have further refined our proof-of-concept design to ensure that the final product is of sufficient purity for use in humans.

**ASTM 2150-17 (9.1.3.3. and 9.1.3.8.) (ISO 10933-5 and 12):** Biological Evaluation of Medical Devices; Tests for in vitro cytotoxicity, Sample preparation and reference materials  
To quantify the degree of cytotoxicity of the given design, this standard could be utilized to perform cytotoxicity testing in vitro.  
In vitro cytotoxicity assays were outside the scope of the requirements of this design but are an important next step that a future design team could implement to gain confidence in the device’s cytocompatibility.

**ASTM 2150-17 (9.1.3.11) (ISO 10933-17):** Biological Evaluation of Medical Devices; Toxicological Risk Assessment  
Prior to achieving FDA clearance for clinical trials to be conducted on this blood-contacting device, a toxicological risk assessment must be performed as described in this standard.  
This standard is a useful guide for assessing systemic toxicologic effects of the final product and should be implemented to test future iterations of this design.

**ASTM 2150-17 (9.1.3.12) (ISO 10933-18):** Biological Evaluation of Medical Devices; Chemical Characterization Testing  
Prior to achieving FDA clearance for clinical trials to be conducted, chemical characterization testing must be performed as described in this standard.  
This standard is a useful guide for assessing the chemical leaching effects of the final product that may occur in vivo and should be implemented to test future iterations of this design.

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### Results

**Figure 6.** A. Inner diameter change of the lumen – 10 minutes of UV-exposure. B. Outer diameter change of the device – 10 minutes of UV-exposure. (n = 1).

The needed 15-18% increase in lumen diameter was achieved in approximately 5 minutes of near UV exposure, and the outer diameter changed less than 1% with 10 minutes of near UV exposure, thus fulfilling both requirements, as seen in **Figure 6A and B**. The hydrogel lumen was not covalently bound to the functionalized PMMA tubing via methacrylation.

95% DexMA extract showed equivalent hemolytic activity compared to LDPE, yielding a hemolytic index of 1.263 (nonhemolytic by extract test), as seen in **Figure 7A.** **Figure 7B** shows that 95% DexMA is 30% of the hemolytic activity of LDPE when directly in contact with blood. This corresponds to a hemolytic index of 0.154 (nonhemolytic by direct contact test). This material is suitable for blood contacting indications as specified by ASTM F756-17 and passes the design requirement.
Figure 7. A. Background Subtracted % Hemolysis of Sample Extracts (PBS (-/-); n = 3; p < 0.001). B. Background Subtracted % Hemolysis of Direct Contact with Sample (n = 3; p < 0.001).

Discussion
The preliminary verification results show promising data; however, the hydrogel contraction experiment should be repeated with a larger sample size because testing was only performed on one sample. Additional experiments to determine the proper surface modification of PMMA is necessary as the hydrogel was very loosely bound to the PMMA tubing. DexMA is shown to be nonhemolytic under ASTM F756-17 and is suitable for blood contacting indications in this design. Overall, our design was successful in achieving the dimensional changes needed to support patient growth in a 5 to 7-minute window of time while being comprised of materials that would not induce hemolysis in the patient. We were unable to acquire a Goretex Propaten Shunt Configured for Pediatrics due to resource limitations, so there was no direct comparison in performance.

F. Conclusions

Project
The first prototype of the design has been developed and has achieved the correct lumen diameter increase in 5 minutes of near-UV exposure. Hemolysis testing was performed on the hydrogel lumen and yielded a nonhemolytic score on the hemolytic index relative to an established negative control biomaterial by ASTM F756-17 for both extract and direct contact testing. Further work must be performed to fix the hydrogel to the outer shunt and expand upon the verification of the hydrogel contraction with a larger sample size.

Future
This preliminary prototype will need several revisions prior to any in vivo testing. The hydrogel must be firmly covalently bound to the outer shunt. Ideally, the final prototype will consist of an expanded polytetrafluoroethylene (ePTFE) shunt with a 95% DexMA hydrogel lumen coating. ePTFE is the material that is currently used in industry for this indication. A method to surface modify ePTFE and introduce free methacrylate groups to which the DexMA could bind needs to be developed. The work involving the plasma treatment could be of use in determining this method. The mechanism by which LAP is incorporated into the hydrogel lumen needs to be elucidated further. Diffusion studies of LAP into and out of the DexMA in an aqueous environment with guidance from ASTM F2900-11 will provide insight into its diffusion coefficient, which will help designers determine if it would be better to incorporate LAP into nanoparticles within the hydrogel structure or to let the LAP diffuse from the catheter with a hollow fiber optic light inserted during the expansion procedure. Additionally, a direct comparison between the current industry standard ePTFE shunt manufactured by W. L. Gore & Associates must be performed to assess toxicity, irritation, and hemocompatibility through ASTM 2150-17 (ISO-10933: 5, 12, 17, and 18).

Impact
When used by the primary stakeholders, who are the healthcare professionals performing the Norwood procedure, this novel shunt design would decrease the number of complications associated with the shunt currently used in the Norwood procedure and eliminate the costs of many revision surgeries. Revision surgeries
constitute a minimum of 30% of all surgeries performed. The revision procedure would be replaced with a significantly less costly procedure in which a catheter is arthroscopically inserted to initiate photo-crosslinking and expand the lumen diameter of the shunt. This innovation has the chance to improve the lives of 1,025 infants born annually in the US with HLHS and cut down on $51.1m/year in healthcare expenses for the current number of revisions performed [8]. By accounting for the changing blood flow in a growing patient with this novel geometrically tunable shunt design, the patient outcome will improve and will mitigate the risk of having to undergo another invasive open-heart procedure.

G. References
May 10, 2020

Dear Dr. Murdock:

We have carefully reviewed the report of their progress, and we approve of its submission to you. We have monitored their work during this academic year, and this team has been incredibly productive.

This team, including Bryan Ferrick, Danika Meldrum, Kristen Shema, and Amber Thomas, is comprised of an interdisciplinary group of senior undergraduate biomedical engineering students having educational concentrations in biomaterials and tissue engineering and biomechanics and human performance. All of these students are high academic achievers, extremely intelligent, and talented. They have a strong work ethic, admirable value system, conscientious character, creative spirit, service mentality, outstanding leadership qualities, and a strong commitment to the advancement of science, engineering, and medicine.

These students have been top performers in their courses, and they will graduate and hold engineering positions at R&D start-ups, prestigious regional companies, and top-Universities in the pursuit of graduate studies. They are leaders among their peers, attend lectures regularly, ask outstanding and thought provoking questions, maintain an enthusiastic and curious attitude, and help their fellow classmates when they struggle. They have demonstrated, during this project, time-and-time again an ability to synthesize complex engineering fundamentals and to apply this information in order to solve challenging problems in cardiovascular and pediatric health.

In this project, they worked to develop a geometrically tunable blood shunt for pediatric patients who are born with severe and significant malformations of their heart chambers. Infants with single ventricle physiology are born with significant structural anomalies which necessitate surgery immediately after birth. In the first of several surgeries, the Norwood, a systemic-pulmonary blood shunt is implanted, which allows the single functional ventricle to drive and draw blood through both the systemic and pulmonary circulations. Despite advancements, the mortality rates for the Norwood are among the highest in the field, and thousands of babies die each year due to complications that arise from this blood shunt. The shunt allows for the mixture of oxygenated and deoxygenated blood, the ratio of which must be carefully balanced to maintain clinical stability. This balance depends heavily on the shunt. Using a fixed shunt during infancy is inherently insufficient, due to vast physiological changes that alter the balance. A geometrically tunable hydrogel based shunt would offer a new approach to adjust the flow ratio, through an expandable inner diameter modified in proportion to growth.
Under the guidance of ASTM standards, this team achieved their objectives to advance the design of a new blood shunt using hydrogel-based and photoinitiated biomaterials. They were creative and innovative in engineering design and troubleshooting challenges that they encountered. They were committed to address this compelling health challenge for children all over the world.


Our Associate Dean for Research and Senior Associate Dean commented that their 2nd term presentation had enough technical content to be the final presentation for the academic year; he was quite impressed with the team and their progress. They have worked incredibly hard on their project, even with the challenges presented by the COVID-19 pandemic and the closing of the University.

Thank you for your award and your support of their research. We are all very appreciative. Please feel free to contact us at Drexel University if you have any questions or comments.

Sincerely yours,

Amy Throckmorton, Ph.D.
Associate Professor

Kara L. Spiller, PhD
Associate Professor

Dr. Randy Stevens, M.D., F.A.C.S.
Attending Cardiothoracic Surgeon, Heart Center of Excellence
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