13th International Workshop on Innovative Simulation for Healthcare, 004
21st International Multidisciplinary Modeling & Simulation Multiconference

2724-0371 © 2024 The Authors.
doi: 10.46354/i3m.2024.iwish.004

3D printed models of the major congenital heart defects: integration into the training of nursing students

Katherine Morrison[1,*], Tracy Lakin[1], Haley Hoy[1], Delaney Enlow[2], Kevin Hernandez[2], Gary Maddux[2] and Bernard Schroer[2]

[1]College of Nursing, University of Alabama in Huntsville, Huntsville AL, 35899 USA
[2]Systems Management and Production Center, University of Alabama in Huntsville, Huntsville AL, 35899 USA

[*]Corresponding author. Katherine.morrison@uah.edu

Abstract

The paper presents the development of 3D printed models (simulators) of a variety of hearts with congenital defects for the training of nursing students in the College of Nursing at the University of Alabama in Huntsville. All the hearts were segmented from CT (computed tomography) or MRI (magnetic resonance imaging) scans. The hearts were printed on a resin printer or a multi-color PLA (polylactic acid) printer to provide a smooth surface and noticeable details. Heart1 was scaled to a small infant heart with an added patent ductus arteriosus (PDA) defect. Hearts2 and 3 were segmented into three slices, with an added atrial septal defect (ASD) and ventricular septal defect (VSD). Heart4 had a disposition of the great vessels (TPG) and Heart5 had a tetralogy of Fallot. Heart6 was an adult heart sliced in halves along the long axis of the heart with all four chambers visible. Similarly, Heart7 was scaled to an adult heart as well. O-ring cord was added to Heart7 to simulate the major arteries and veins. Hearts8-10 were identical to Hearts1, 2 and 7 and printed in multi-color PLA (polylactic acid) filament. The congenital heart defects in Hearts4 and 5 were difficult for students to locate and see. Consequently, these hearts were not included in the training. Instead, the ASD and VSD defects were added using Fusion360 to the appropriate hearts. The faculty and students preferred 1) infant Heart1 with ductus arteries, 2) Heart2 slice with ASD and VSD defects, 3) adult Heart6 sliced vertically with ASD and VSD defects and most notably, 4) the multi-color 3D printed hearts

Keywords: 3D printed models, congenital defect, simulator, infant heart, hole in heart, heart models

1. Introduction

Simulation is an effective method for training health care professionals to perform patient procedures. Task trainers are models of varied fidelities to simulate specific procedural skills and often utilized in medical simulation (Lichtenberger et al., 2018).

A study by Asif et al. (2021) of 587 medical students, post graduate trainees and clinical staff stated that participants using 3D printed models demonstrated improved test scores and faster procedural completion rates for identifying anatomical landmarks as compared with traditional teaching methods. Some of the benefits of 3D printed technology are exposure to procedures that would not ordinarily be experienced through routine clinical operations and greater user self confidence in understanding medical concepts. Those who used 3D printed models reported improved subject understanding and increased confidence in reporting the pathology. Participants felt that 3D printed models were more useful than diagrams and videos (Su etal., 2018 and Costello etal, 2015).

Karsenty et al. (2023) interviewed 76 parents that were divided into a group of 38 that was given

© 2024 The Authors. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY-NC-ND) license (https://creativecommons.org/licenses/by-nc-nd/4.0/).

interventional cardiac catheterization instruction and shown 3D printed models of the heart and a group of 38 that received only instructions. Most (35 of 38 parents) found the 3D printed models extremely useful. The use of 3D printed models is being used to detect abnormal heart structures and heart attacks. Vukicevic et al. (2017) have outlined the use of 3D printing in cardiovascular care, especially for heart disease.

Congenital heart defects are structural problems arising from abnormal formation of the heart or major blood vessels. This paper presents the development of the 3D printed models of the heart with the following five major congenital conditions: 1) patent ductus arteriosus (PDA), 2) atrial septal defect (ASD), 3) ventricular septal defect (VSD), 4) transposition of the great vessels (TGV) and 5) tetralogy of Fallot (American Heart Association, 2021).

1.1. College of Nursing

The College of Nursing offers RN-BSN, BSN, MSN, DNP and a PhD in Nursing, as well as a Post Masters Family Nurse Practitioner Certificate and a Graduate Certificate in Nursing Education. In 2022 enrollment was 964 students with 581 undergraduate and 383 graduate students. In 2022 302 degrees were awarded with 160 bachelors, 121 masters, 7 certificates and 14 doctoral degrees.

The CoN Simulation & Learning Innovation Center (SLIC) occupies over 10,600 sqft. SLIC holds a sixteen bed hospital laboratory, a sixteen table assessment room, collaboration stations, four advanced practice provider clinical examination rooms, a telehealth room, a Pyxis medication room, and debriefing rooms. SLIC provides a mock hospital for clinical experiences, including seven high fidelity simulation laboratories with digital video and audio management systems, four medical-surgical suites, an ICU suite and an obstetric/pediatric four-bed laboratory.

1.2. Research objective

The research objective of this project was to develop 3D printed models of the major congenital heart defects for training undergraduate and graduate nursing students in the College of Nursing (CoN) at the University of Alabama in Huntsville (UAH). Factors considered in the model development were 1) model fidelity, 2) axial (horizontal) and vertical slices of the models, 3) model color, 4) windows to look at the valves inside the heart and 5) the ability of nursing students to locate and identify the congenital heart defects. Included in this paper are 1) a description of the major congenital heart defects, the development of the 3D printed models, 3) the issues in detecting the defects in the models and 4) the use of the models in the classroom.

2. Background

The heart has four chambers that pump blood (Figure 1) (Cleveland Clinic, 2023):

- Right atrium receives oxygen poor blood and pumps blood to the right ventricle through the tricuspid valve.
- Right ventricle pumps blood to the lungs through the pulmonary artery. The blood picks up oxygen in the lungs and moves blood through the pulmonary valve which closes when the chamber relaxes between beats.
- Left atrium receives the oxygen rich blood from the lungs and sends blood through the pulmonary veins and mitral valve and into the left ventricle.
- Left ventricle pumps the oxygen rich blood to the rest of the body through the aorta. The blood passes through the aortic valve which closes when the left ventricle relaxes.

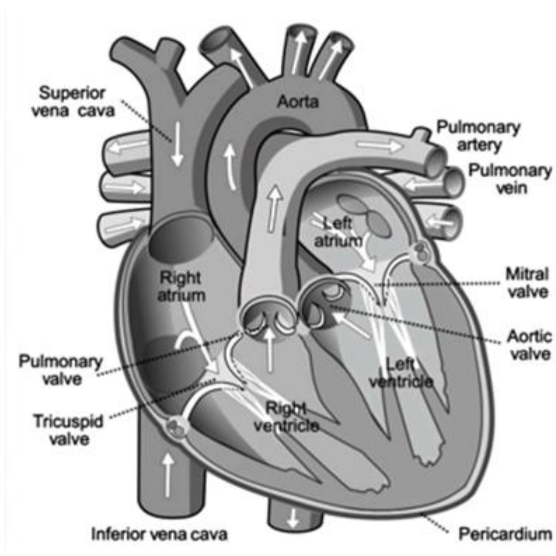

Figure 1. Chambers of the heart (Cleveland Clinic, 2023).

2.1. How baby's heart works before birth

Since the baby in the womb is not breathing there is no need to pump blood to the lungs. Oxygen rich blood is moved from the mother to the baby using the placenta and umbilical cord. The oxygen rich blood then goes to the right atrium through the inferior vena cava vein and then across the foramen ovale and into the left atrium. The blood then enters the left ventricle and is pumped throughout the body.

The foramen ovale allows oxygenated blood from the umbilical cord to flow directly from the right atrium to the left atrium, instead of the blood going to the right ventricle and lungs which is the case for adults. The ductus arteriosus connects the pulmonary artery to the aorta, allowing the fetus's oxygenated blood to detour away from the lungs and directly to the aorta (Live Science, 2023).

2.2. Patent ductus arteriosus (PDA)

Before birth the right side of the heart is dominant in sending blood through the body. After birth the circulatory system rearranges and the left ventricle becomes dominant. The oxygen rich blood now comes from the lungs into the left atrium. The pressure of the blood pumping through the heart usually forces the flap opening of the foramen ovale to close. Now the right ventricle sends oxygen poor blood to the lungs (Clark et al., 2023).

After birth the ductus arteriosus is not needed and closes within several days. However, in some infants the ductus arteriosus does not close. When it stays open it is called a patent ductus arteriosus (PDA). The PDA causes blood to flow back from the aorta to the pulmonary artery which decreases the amount of oxygenated blood sent out to the body (Figure 2) (Mayo Clinic, 2023).

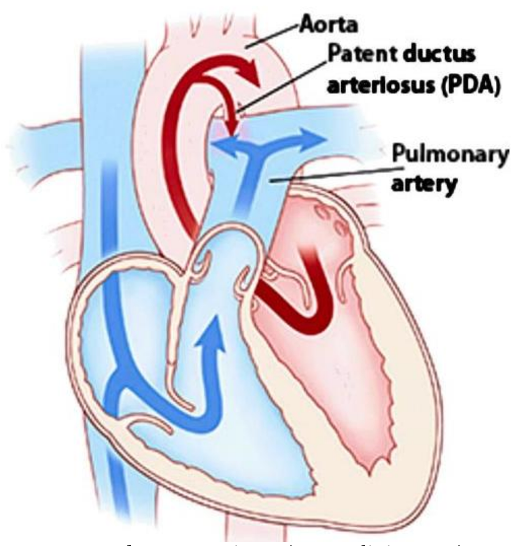

Figure 2. Patent ductus arteriosus (Mayo Clinic, 2023).

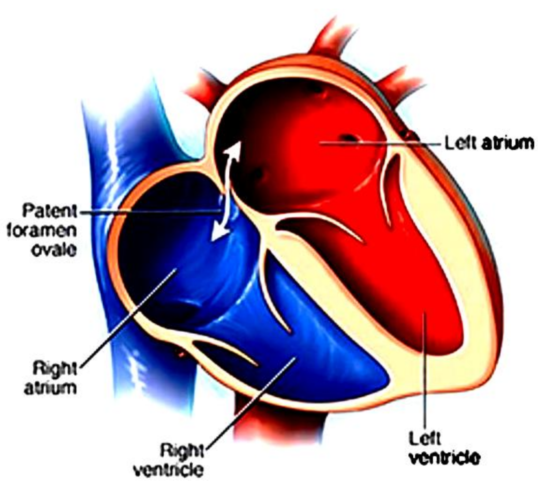

Figure 3. Patent foramen ovale (PFO) (Mayo Clinic, 2023).

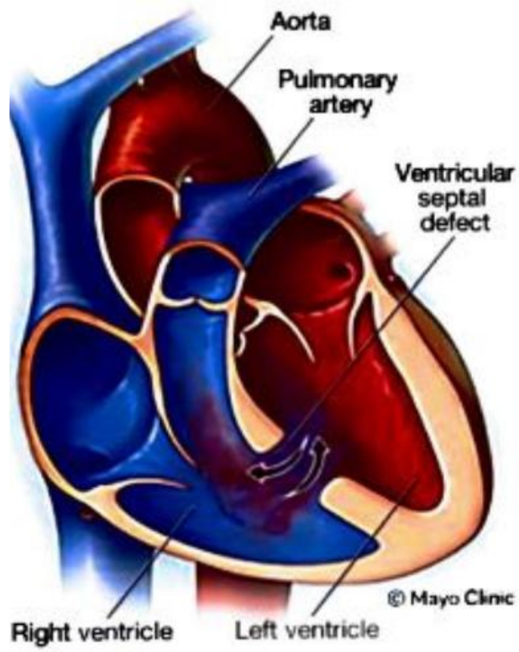

Figure 4. Ventricle septal defect (VSD) (Mayo Clinic, 2023).

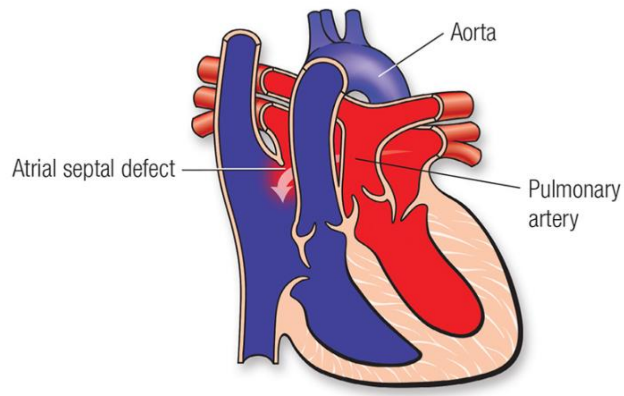

Figure 5. Transposition of great vessels (American Heart Association, 2023).

2.3. Atrial septal defect (ASD)

The septum separates the right and left chambers. An atrial septal defect (ASD) occurs when the atrial septum wall does not grow completely before a baby is born.

Patent Foramen ovale (PFO) is an anatomical variant of the ASD. In a normally growing fetus a flap like opening called a foramen ovale is present in the wall of the heart that serves to shunt the blood between the two upper chambers of the heart, the right atrium and the left atrium. After birth the lungs begin to function which increases the blood pressure in the left atrium. The foramen ovale typically closes during infancy. When the foramen avole does not close it is called a patent foramen ovale (PFO). PFO occurs in about one in four people.

Most people never know they have this condition (PFO) since the PFO is smaller than the hole from an atrial septal defect (Heart Institute, 2023). A patent foramen ovale is often discovered during tests for other problems (Figure 3) (Mayo Clinic, 2023).

2.4. Ventricular septal defect (VSD)

A ventricular septal defect is a hole that occurs in the interventricular septum wall that separates the right and left ventricles (Figure 4). It is a common problem present at birth (congenital heart defect) that allows oxygen rich blood to move back into the lungs instead of being pumped to rest of body (Mayo Clinic, 2023). Many small ventricular septal defects close on their own. Larger defects may need surgery early in life to prevent complications.

2.5. Transposition of great vessels (TGV)

The transposition of the great vessels, or the transposition of the great arteries, is a serious but rare heart defect present at birth and is the reversal of the aorta and pulmonary artery. The aorta is connected to the right ventricle rather than the left ventricle, while the pulmonary trunk is connected to the left ventricle rather than the right ventricle (Figure 5) (American Heart Association, 2023). Consequently, the transposition of the great arteries alters the circulation of blood. Oxygen poor blood goes to the body instead of the lungs and oxygen rich blood goes to the lungs instead of the body.

2.6. Tetralogy of Fallot

Tetralogy of Fallot is a combination of the following four heart defects at birth: 1) a ventricle septal defect (VSD), 2) a narrowing of the pulmonary valve and main pulmonary artery, 3) an enlarged aortic valve that allows blood from both ventricles to enter and 4) a thicker than normal right ventricle (right ventricular hypertrophy).

3. Materials and Methods

The following STL (stereolithography) files of hearts were located:

- Heart1 file from Embodi3D and developed by Marco Vettorello, MD, anesthesiologist and intensive care physician. Fusion360 was used to scale the heart to an infant heart and to include a ductus arteriosus.
- Heart2 file from Embodi3D and Fusion360 was used to include a patent foramen ovale (PFO) and a ventricle septal defect (VSD).
- Heart3 file from Embodi3D and was developed by Mathew Bramlet, MD, pediatric cardiologist. The file already had a ventricle septal defect (VSD). The model was segmented from a MRI (magnetic resonance imagining) scan of a three year old.
- Heart4 file was also from Embodi3D and developed by Mathew Bramlet, MD, pediatric cardiologist. The model showed the transposition of the aorta and pulmonary artery.
- Heart5 file from Embodi3D and developed by Mathew Bramlet, MD, pediatric cardiologist. The model showed a combination of four heart defects (tetralogy of Fallot) at birth as previously shown above. The model was segmented from a CT (computed tomography) scan of a four year old.
- Heart6 file was from Embodi3D and developed by Michael Itagaki, MD, practicing interventional radiologist and founder of Embodi3D. This model was created from a high quality CT scan.
- Heart7 was the scaling of Heart1 (before adding the DA) to correspond with an adult heart.

All the models were printed on one of three 3D printers. The Elegoo Saturn2 resin printer has a build volume of 19.2x12x20cm. Resin printers use a photocuring UV (ultraviolet) resin as the print medium. A UV light source cures the resin causing the resin to harden and sticks to the previous layer. The build plate then rises and the process repeated. After printing the model needs to be washed and cured. Several advantages of resin printing are model smoothness and greater detail.

The second printer was a Prusa-i3 MK3S with PLA (polylactic acid) filament that had a build volume of 25x21x21cm.

The third printer was a Bambu Lab X1-Carbon four-color printer with PLA filament and a build volume of 25.6x25.6x25.6cm.

A 1.75mm diameter PLA filament was initially fused to the Heart1 model to simulate the ductus arteriosus. Upon approval by the College of Nursing faculty the ductus arteriosus vessel was added to the model using Fusion360 software.

The heart of a newborn is the size of a large walnut. Khir etal, (2012) studied three varieties of walnuts and determined the diameters for the varieties to be 30.98-40.50mm, 25.11-37.40mm and 27.78-36.91mm. Heart1 was printed at 40%, 50% and 60% of the full size model. The 40% Heart1 closely matched the size of a newborn heart and measured approximately 40mm in diameter and 55mm in vertical length. Figure 6 is a 3D printed model of Heart1 with ductus arteriosus.

Figure 6. 3D printed model of Heart1 (40%) with ductus arteriosus.

4. Results and Discussion

The 3D printing statistics are given in Table 1. Three Heart1s were printed on one build plate. Likewise, all three slices for Heart2, 3, or 5 were printed on one build plate as well. Heart4 was too large for one build plate, consequently the material costs were more and the print time increased significantly.

Heart6 was much larger and each half had to be printed separately on the build plate. Therefore, the total print time for both halves was over twenty hours.

Table 1. 3D printing data.

Heart	Print time	Cure time	Resin	Cost
Heart1 (printed 40%, 50% and 60% hearts at once)				
	8hr 51min	7min	215ml	$2.50
Heart2 (printed three slices at once)				
	4hr 30min	6min	155ml	$5.40
Heart3 (printed three slices at once)				
	4hr 23min	6min	151ml	$5.14
Heart4 (printed three slices at once)				
	8hr 9min	9min/slice	337ml	$11.11
Heart5 (printed three slices at once)				
	5hr 10min	5min	56ml	$1.84
Heart6 (printed top slice only)				
	10hr 22min	9min	215ml	$7.10
Heart6 (printed bottom slice only)				
	9hr 25min	8min	130ml	$4.27
Heart7 (adult heart)				
	8hrs	8min	316ml	$9.48

Heart	Print time	PLA	Cost
Heart8 (Heart1 printed with four PLA colors)			
	43hr 51min	659g	$19.77
Heart9 (Heart2 printed with two PLA colors)			
	26hr 3min	454g	$13.62
Heart9	(valves)		
	2hr	9g	$0.27
Heart10 (Heart7 adult heart printed with two PLA colors)			
	33hr 3min	621g	$18.63

The CoN faculty selected a slice from Heart2 using the 3D rendering capability of Fusion360 to show the four heart chambers. After printing several models of Heart2 the faculty requested a 4mm hole added in the septum between the right and left atrium to simulate an atrial septal defect (ASD) and a 4mm hole in the septum between the right and left ventricles to simulate a ventricle septal defect VSD). Figure 7 shows both septal defects.

Figure 8 shows the three slices of Heart3 with the left slice showing the VSD defect which was added with Fusion360. As a note the defect diameter can vary from the size of a pin to the complete absence of the ventricular septum.

Figure 9 shows the three slices of Heart4 with the transposition of the aorta and pulmonary artery. The faculty requested that the three slices be combined and printed as one model. However, showing the transposition to students was difficult using both models.

Heart5 with the tetralogy of Fallot was also difficult to detect.

The print time for Hearts8-10 with multi-color PLA took considerably more time than a one-color resin heart. For example, adult Heart10 took 310% longer to print and material cost increased 97% as compared with Heart7.

The nursing faculty stated that all the defects were difficult to locate. Hearts3-5 were sliced axially (horizontally) which did not help in locating the defects. Furthermore, the heart models did not have any readily locatable features, such as a well defined aortic arch, to assist in orientation.

Figure 7. Slices of Heart2 with added ASD and VSD using PLA filament.

Figure 8. Axial slices of Heart3 with VSD (left slice) using resin.

Figure 9. Axial slices of Hwart4 with TGV using resin.

Figure 10. Heart6 printed using resin.

Heart6 was printed to assist nursing students in the orientation of the heart. Figure 10 is Heart6 printed using a white resin. Figure 11 shows the two slices along the long axis of Heart6; therefore, all four chambers are visible, in addition to the superior vena cava, inferior vena cava and pulmonary arteries and veins. ASD and VSD defects were added to the model using Fusion360.

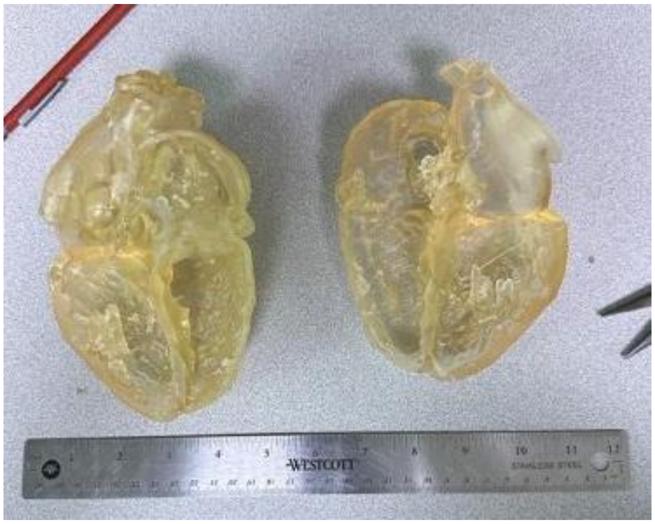

Figure 11. Heart6 sliced in half along vertical axis in clear resin..

Heart1 is the same as the initial Heart0 without the ductus arteriosus. Heart7 is the scaling of Heart0 to correspond to an adult heart. A typical adult heart is about the size of two clenched fists while a child's heart is about the size of one clenched fist (Cleveland Clinic, 2023). The shape of an adult heart is similar to that of a pine cone and approximately 120mm in length (from the bottom of the aortic arch to the apex), 80mm in width (widest part of heart) and 60mm in thickness (Hartline, 2023). Heart7 was scaled using Fusion360 resulting in the heart dimensions of 110mm in length, 85mm in width and 80mm in thickness.

Figure 12 shows Heart7 3D printed in red resin. The brachiocephalic trunk and the left subclavian trunk were added to the aortic arch. Two additional trunks were added for the right and left interior and exterior jugular veins. The trunks were designed in Fusion360 and 3D printed in PLA filament. A white o-ring cord was added to simulate the major arteries and veins rising from the heart. The red sleeves are arteries and the blue sleeves are veins. The diameters of these vessels are close to full scale.

Hearts1, 2 and 7 were also printed in multi-colored PLA. The infant Heart8 (Heart1) was printed in four colors: red representing oxygenated blood, blue for deoxygenated blood, purple for a mix of oxygenated and deoxygenated blood and yellow for the ductus arteriosus (Figure13).

Heart9 is an adult version of Heart2 and printed in two colors. Two of the valves were printed in blue PLA and were removable (Figure 14). Heart10 is the adult version of Heart7 and printed in two colors (Figure 15).

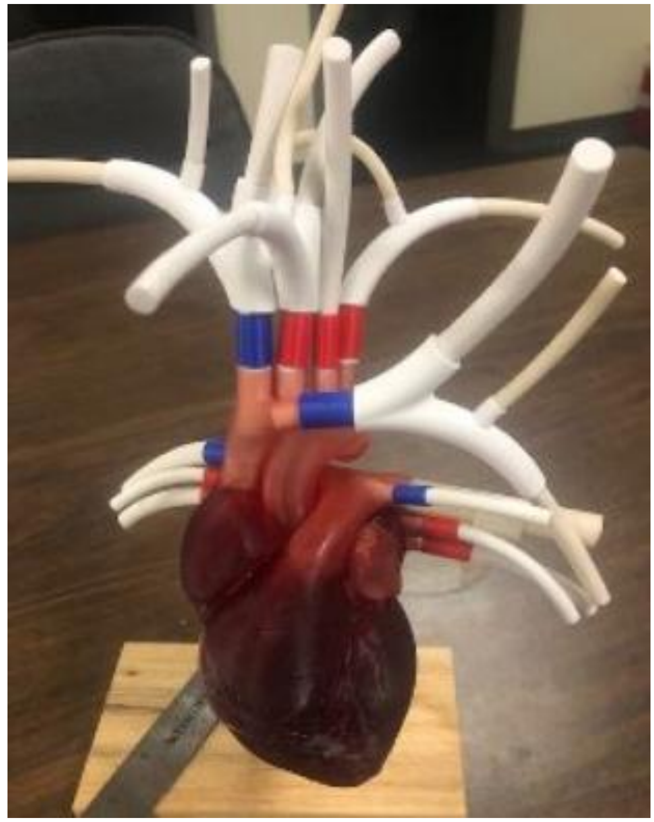

Figure 12. Adult Heart7 printed in red resin.

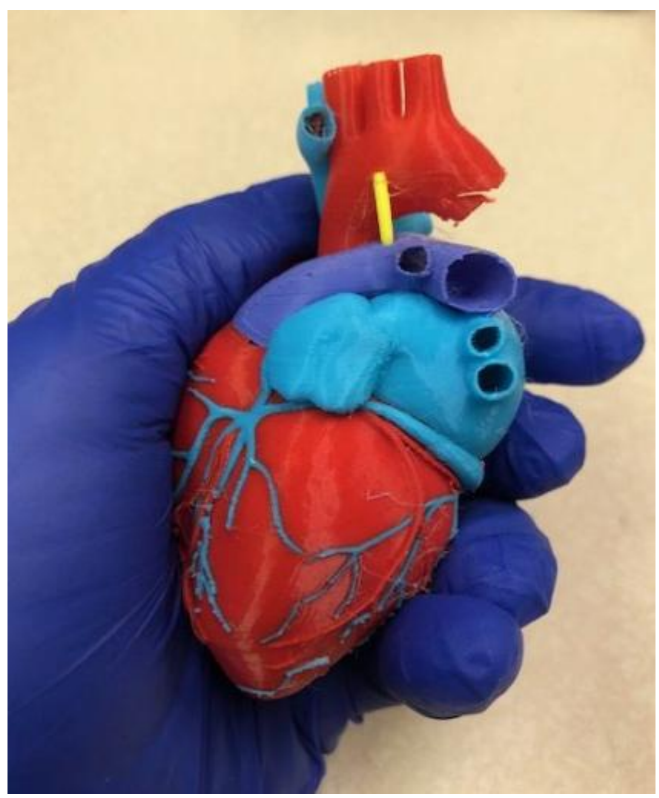

Figure 13. Infant Heart8 printed in multi-colors showing arteries and veins using PLA filament.

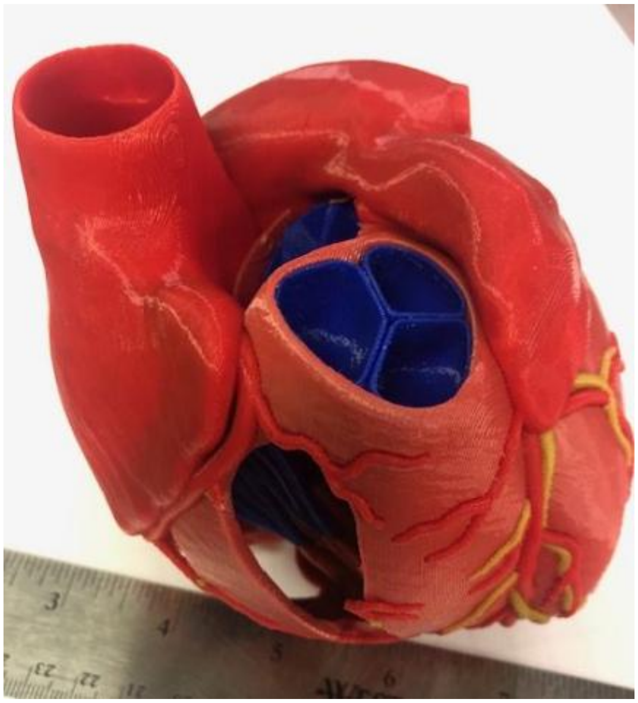

Figure 14. Heart9 with removable valves using PLA filament.

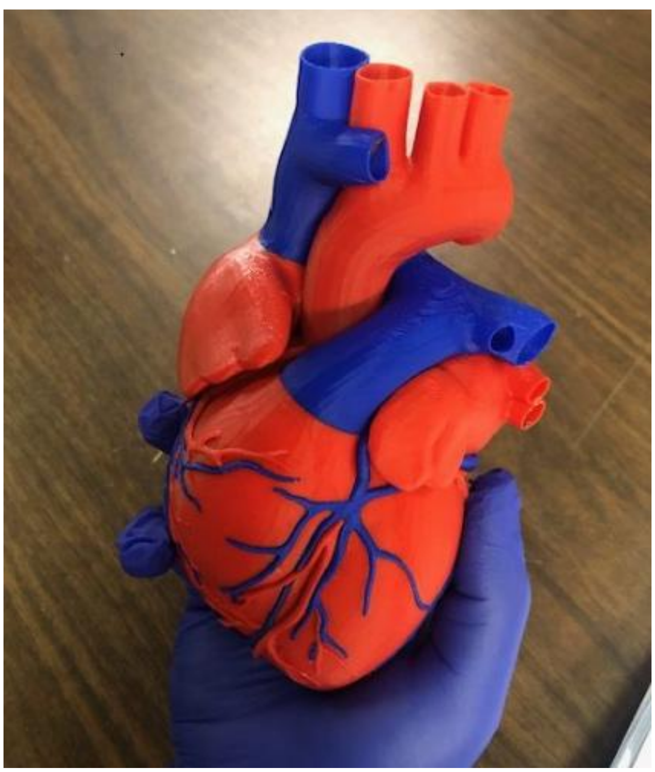

Figure 15. Adult Heart10 printed using PLA filament.

5. Conclusions

No infant heart model with a ductus arteriosus was readily available. Therefore, an adult heart was scaled and a ductus arteriosus was added with Fusion360 software (Heart1).

The atrial septal defect (ASD) and ventricular septal defect (VSD) were difficult to locate in the 3D printed models and therefore difficult for training nurses. This difficulty was solved by adding several small round holes to the slices in Hearts2, 3 and 6 to simplify locating the defects.

The transposition of the aorta in Heart4 and the tetralogy of Fallot in Heart5 were very difficult to detect. These 3D printed models were not used for instruction.

Heart6 was a full scale adult heart segmented from a CT scan. This heart was sliced longitudinally to show the four chambers. ASD and VSD defects were easily added to the model using Fusion 360.

Adult Heart7 was printed in a red resin, giving it a more realistic look. An o-ring cord was added to simulate arteries and veins.

Several of the valves in Heart2 were segmented and printed on a multicolor 3D printer to enhance nurse training (now labeled Heart9). Heart10 was the printed and colorized version of Heart7.

The multi-colored infant Heart8 was preferred over the white and clear resin, especially for the red PLA representing oxygenated blood, blue for deoxygenated blood, purple for a mix of oxygenated and deoxygenated blood and yellow for the ductus arteriosus.

Multiple copies of the hearts were 3D printed, thus permitting faculty to share the models with students during training. The heart models were used in the classroom to supplement learning traditionally provided by lecture and illustrations. The models added fidelity and were superior to the illustrations alone by providing 3D visual orientations of the heart. The scaling of the hearts to infant and child size added to the fidelity.

Congenital heart defects were difficult for the students to locate in the heart models. One difficulty that was encountered was that the heart is not perfectly symmetrical due to the complexity of the natural structures. Therefore, providing the heart slices gave students a better understanding of the anatomy as compared to flat images commonly used in illustrations or the typically bisected heart.

Photocuring UV (ultraviolet) resin provided high quality, smooth and great detailed 3D printed models. Model clean up was minimal with very little waste, as compared to polylactic acid (PLA) filament for fused deposition modeling (FDM) printers. Material cost for a heart ranged from $2.50 for an infant Heart1 to $11 for an adult Heart6.

The models were used in the undergraduate pediatric specialty course. This fourth semester upper division course teaches students to apply nursing concepts to pediatric patients in the healthcare system. Learning outcomes for the perfusion module included 1) comparing anatomic and physiologic differences of the cardiovascular system in infants and children versus adults and 2) distinguishing cardiovascular disorders common in infants, children, and adolescents. The whole heart model showing the PDA in the infant heart (Heart1) and the models for ASD and VSD were used to supplement the lecture and illustrations.

Use of the models allowed the students to see the 3D visual representations of the heart with the associated defects in order to compare the anatomic structures and rationalize the physiologic changes that occur with each defect, thus meeting the first learning outcome. Once the anatomic and physiologic outcomes were realized, the students could then better understand the different cardiovascular disorders that infants and children may demonstrate related to the associated defects.

Anecdotal feedback from the students was positive. Students responded well to the models and were visibly engaged with the models during the lecture. Further research is needed to explore what impacts were made on the student learning and testing.

The models have been used in multiple graduate level classes. In the Adult Gerontology Acute Care Nurse Practitioner (AGACNP) program, the models have been used in the first and second clinical classes. In AGACNP I, the models were used as a refresher before delving into the vascular system. Students were each given a heart (see figure 12) to label and then asked to describe the flow of blood through the heart.

The students were allowed to keep the hearts they labeled for future assignments. In AGACNP II, the multicolored hearts with valves and chordae were used to demonstrate skills. Students were able to hold the hearts and place cardiac pacemaker (PM) and internal cardiac defibrillator (ICD) leads in the correct position in order to gain an understanding of how PMs and ICDs work as well as identify potential causes of device failure such as lead misplacement.

Transcatheter Aortic valve replacement (TAMR) and Transcatheter Mitral valve replacement are two relatively new procedures in the United States. By having the multicolored hearts with valves, students were able to see where and how the balloon valves are deployed.

Students could also identify potential sequelae from TAVR and TAMR and the pathophysiology that causes the problem. An example of a potential sequelae is bradycardia from the deployment of a TAVR valve. The TAVR valve can occlude or obstruct the sinoatrial node leading to bradycardia or heart blocks. The use of visual and kinetic learning tools greatly improves the understanding of the pathophysiology and potential sequelae that students will encounter in practice. A formal evaluation of the students' perception of using the hearts will be performed in the future.

In conclusion,

- 3D printed models can be readily made of the major congenital heart defects provided that a high quality CT or MRI scan is available. However, for training nursing and nurse practitioner students the location and identification of these heart defects was difficult and quite often impossible.
- No model was located of the ductus arteriosus (DA). Adding the DA was readily added in the form of a small tube with CAD software.
- The atrial septal defect (ASD) and ventricular septal defect (VSD) were readily added by inserting small holes in the septum that divides the right and left chambers of the heart with CAD software.
- The 3D printed models of the transposition of the great vessels and the tetralogy of Fallot heart defects were very difficult to locate and identify and consequently were not usable by the nursing faculty.
- Heart slice orientation, heart detail and heart color were important factors in teaching congenital heart defects. Both horizontal (axial) and vertical slices of the 3D printed hearts were effective in highlighting the added holes simulating ASD and VSD. 3D printed hearts that had considerable model cleaning and added detail, such as coronary arteries that cover the exterior surface of the heart, were the most requested hearts for training purposes.
- Many of the 3D printed hearts were provided to the students for personal use. Windows, or openings, were 3D printed on the exterior surface of several of the hearts to expose the interior of the heart and heart valves.
- Hearts that were 3D printed in multi colored filament provided the “wow” factor. Arteries were printed in red representing oxygenated blood, blue for deoxygenated blood, purple for a mix of oxygenated and deoxygenated blood and yellow for the ductus arteriosus. The only drawback to color is the significant increase in the print time.

Acknowledgements

This project was supported by The University of Alabama in Huntsville (UAH) Systems Management and Production Center and The UAH College of Nursing.

References

American Heart Association (2011). Patent foremen ovale (PFO), *Stroke Connection Magazine,* www.heart.org, Jan/Feb.

American Heart Association (2023). Common types of heart defects, *American Heart Association,* www.heart.org

Asif, A., Lee, E., Caputo, M., Biglino, G. and Shearn, A. (2021). Role of 3D printing in pediatric teaching and training: a systematic review, *BMJ Paediatrics Open*, 5(1), Dec 7.

Clark, S., Yoxall, C. and Subhedar, N. (2023). Measurement of right ventricular volume in healthy term and preterm neonates, *Archives of Disease in Childhood Fetal & Neonatal*, 87 (2).

Cleveland Clinic, (2023). Hearts, *Cleveland Clinic, www.my.clevelandclinic.org.*

Costello, J., Olivieri, L, Su, L., etal (2015). Incorporating three-dimensional printing into a simulation-based congenital heart disease and care training curriculum for resident physicians. *Congenital Heart Disease,* 10, pp185-90.

Hartline, R. (2023). Location, size and shape of the heart, *LibreTexts Biology*, www.libretexts.org.

Heart Institute (2023). Atrial septal defect and patent foramen ovale, *Heart Institute, Intern Mountain Health,* www.intermountainhealthcare.org.

Karsenty, C., Hadeed, K., Djeddai, C., etal (2023). Impact of 3D printed models in meeting with parents of children undergoing interventional cardiac catheterization, *Frontiers in Pediatrics*, 10, Jan 9.

Khir, R., Pan, Z., Atungulu, G. and J. Thompson (2012). Characterization of physical and aerodynamic properties of Walnuts, *Proceedings ASABE, American Society of Agricultural and Biological Engineers*, Jan.

Lichtenberger, J., Tatum, P., Gada, S., Wyn, M., Ho, V. and Liacouras, P. (2018). Using 3D printing (additive manufacturing) to produce low-cost simulation models for medical training, *Military Medicine,* 183 (suppl 1) 73-77, Mar-Apr.

Live Science (2023). What happens when a baby takes its first breath, *Life Science,* www.lifescience.com.

Mayo Clinic (2023). PDA, PFO, VSD, *Mayo Clinic for Medical Education and Research*, www.mayoclinic.org.

Storm, M. (2018). PDA, PFO and fetal circulation, *Storm Anesthesia Review*, 2nd edition, www.stormesthesia.com

Su, W., Xiao, Y., He, S., Huang, P. and Deng, X. (2018). Three-dimensional printing models in congenital heart disease education for medical students; a controlled comparative study, *BMC Medical Education*, 18, pp 1-6.

Vukicevic, M., Mosadegh, B., Min, J. and Little, S, (2017). Cardiac 3D printing and its future directions, *JACC: Cardiovascular Imaging,* 10(2), 171-184, Feb.

Wikipedia (2023). Tetralogy of Fallott, *Wikipedia,* www.wikipedia.com.

Yap, Y. and El-Feky, M. (2023). Ventricular septal defect, *Radiopaedia,* www.radiopaedia.org , Jul.