

Development of 3D-Printed Congenital Heart Disease Models Using Feasible Low-Cost Workflow – A Potential Tool to Improve Pediatric Cardiology Education

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Abstract

Background: Congenital heart diseases (CHD) require an in-depth anatomopathological understanding. 3D printing is a promising educational tool for creating physical prototypes from imaging data, but costs are a major issue.

Objective: This study aimed to describe a feasible low-cost workflow for the development of 3D-printed (3DP) CHD models and create a shareable educational set.

Methods: Data from cardiac tomography images were used, following the steps of image acquisition, segmentation, digital design, slicing, 3D printing, and post-printing. Valvar structures were created from echocardiographic data using the cartographic heightmap technique and inserted into prototypes. 3DP models were evaluated by an expert team, enhanced, and applied to medical residents during an educational session. Free software, a desktop 3D printer, and low-cost materials were used.

Results: Twelve 3DP models were developed, including ventricular septal defect with patent ductus arteriosus, atrial septal defect, Tetralogy of Fallot, transposition of the great arteries, atrioventricular septal defect, coarctation of the Aorta, hypoplastic left heart syndrome, tricuspid atresia, pulmonary atresia, total anomalous pulmonary venous connection, *Truncus arteriosus*, and interrupted aortic arch. All residents (100%) agreed that prototypes were “faithful to the anatomy”, “visually appealing”, “motivated the study”, and “allowed better spatial conceptualization”. They related 3DP CHD models “are an important pedagogical resource” and can potentially benefit the education of “undergraduate students” (100%), “interdisciplinary team” (100%), “cardiologists, surgeons and residents” (100%), and “families” (93%).

Conclusion: Development of 3DP CHD models using a low-cost workflow is feasible. Models developed are freely available for download and printing, intending to promote education to all interested in CHD.

Keywords: Three-Dimensional Printing; Congenital Heart Defects; Cardiology.

Introduction

Cardiology and pediatric cardiovascular surgery require profound anatomopathological understanding, and the ability to build three-dimensional mental representations is critical for complete comprehension of congenital heart disease (CHD).¹

The capability to create physical prototypes from imaging exams, such as computed tomography (CT), made 3D printing

a valuable tool. Applications of 3D printing in congenital heart surgery can be divided into clinical applications for surgical decision making and planning, preoperative surgical simulation and computer-aided design of surgical baffles and patches, and educational applications like hands-on surgical training, congenital heart morphology teaching, and patient and family education.² This rapidly evolving technology has been reshaping and improving processes, potentially benefiting all involved in children’s heart care.

Many conditions can limit the use of 3D printing technology in low-resource settings. Establishing a hospital-based 3D printing center needs careful financial planning due to the substantial costs involved. Annual expenses for software licenses can exceed €10,000, while high-performance 3D printers may cost upwards of €150,000.³

This study aimed to develop a set of 3D-printed (3DP) CHD models, representative of the more prevalent CHD, detailing a feasible low-cost workflow that can be reproduced by any

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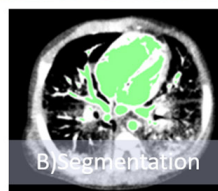
Manuscript received June 14, 2025, revised manuscript July 14, 2025, accepted October 01, 2025

Editor responsible for the review: Nuno Bettencourt

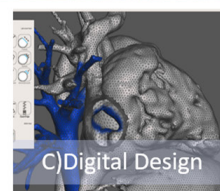
DOI: <https://doi.org/10.36660/abc.20250419i>

Central Illustration: Development of 3D-Printed Congenital Heart Disease Models Using Feasible Low-Cost Workflow – A Potential Tool to Improve Pediatric Cardiology EducationABC Cardiol
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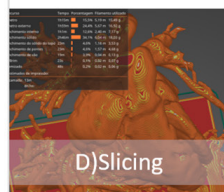
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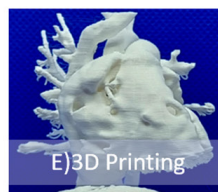
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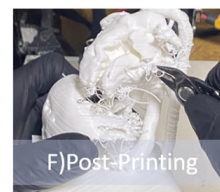
C)Digital Design



D)Slicing



E)3D Printing



F)Post-Printing

Arq Bras Cardiol. 2026; 123(1):e20250419

Workflow proposal using free software, a desktop 3D printer, and affordable materials. 1: Cardiac image acquisition; 2: Segmentation - InVesalius® 3.1; 3: Digital design - AutoDesk® Meshmixer™ 3.5.474; 4: Slicing - PrusaSlicer® 2.4.2; 5: 3D printing - Creality® Ender-3™ 3D printer; 6: Post-printing.

researcher in low-resource settings, and share the models for educational purposes.

Methods

Ethical Aspects

The study was submitted to Plataforma Brasil with the Certificate of Presentation for Ethical Appreciation number 48575021.3.0000.5415 and approved by the Ethics Committee of the Faculdade de Medicina de São José do Rio Preto on July 9, 2021. The study was concluded in 2024. All image data were gathered from the institutional image database of CHD patients under two years old who had previously undergone

complementary investigation for diagnostic elucidation or perioperative planning. No children were identified, specifically recruited, or subjected to a new scan for research purposes. Therefore, there was no requirement for patient consent forms due to the retrospective nature of data collection. Regarding the reviewers, all were submitted to the Informed Consent Form.

Development of 3D-printed CHD models

Selection of cases considered the global prevalence of CHDs⁴ and the data available from the Pediatric Cardiac Radiology collection of CardioPedBrasil® files.

CHD selected for 3D prototyping were ventricular septal defect (VSD), patent ductus arteriosus (PDA), atrial septal

defect (ASD), *Tetralogy of Fallot* (TOF), transposition of the great arteries (TGA), atrioventricular septal defect (AVSD), coarctation of the Aorta (CoA), hypoplastic left heart syndrome (HLHS), tricuspid atresia (TriAtr), pulmonary atresia (PulmAtr), total anomalous pulmonary vein connection (TAPVC), *Truncus Arteriosus*, and aortic arch interruption (IAA). We sought optimal CT image acquisitions, looking for high-quality processing during manufacturing steps, and selected the best CT image pool for each CHD. Although every CHD has many subtypes, we sought to find one representative case of each disease.

Development followed the recommendations of the 3D Printing Special Interest Group (SIG) of the Radiological Society of North America (RSNA)⁵ and is summarized in the Central Illustration.

Image acquisition

Institutional protocol for pediatric cardiac CT acquisition states IV iodinated contrast Guerbet-HenetiX® 350mg/ml, 1.5-2.0 ml/kg at 2.0-3.0 ml/s infusion pump speed rate. Acquisitions: scout, non-enhanced contrast, pre-monitoring phase, arterial phase (80 kV voltage, tube current 120mA/s, axial protocol, 0.5s 360° tube rotation, pitch 1.375, 1.0mm slice thickness, volumetric reconstruction ratio 0.625/0.312), late arterial (or early venous) phase (3-6 seconds after arterial acquisition), and late venous phase. All patients had anesthesiologic support during CT scans.

Segmentation of areas of interest

Consists of the conversion of hundreds of 2D (x,y cartesian axes data) CT DICOM images to a 3D voxel matrix (x,y,z cartesian axes data), allowing continuity to the 3D volume modeling workflow. Invesalio® 3.1 software semiautomatically permitted the selection of regions of interest (ROI) and performed digital extraction. DICOM files were imported, areas between 440-1300 HU were selected, and every image acquired was optimized for a less raw final voxel 3D matrix. The final product was converted and exported to STL extension.

Accurate cardiac segmentation and the selection of areas of interest rely on the expertise of the operators in both the CHD morphology and digital image processing. While artificial intelligence can significantly accelerate and automate this process, the high costs of commercially available platforms may limit the feasibility of establishing a 3D printing service in resource-limited hospital settings. Fortunately, there are free tools capable of converting DICOM into compatible STL or object file wavefront (OBJ) extensions, such as InVesalio®, 3DSlicer®, 3DView®, Horos®, ImageJ®, The Medical Imaging Interaction Toolkit®, ITK-Snap®, and Seg3D®.

3D modelling

Once segmentation is complete, the resulting 3D volume undergoes processing in computer-aided design (CAD) software. At this stage, it is possible to eliminate irrelevant residual anatomic structures, and the rendering process allows editing, modeling, refining, filling, smoothing, inspecting, and correcting flaws that could affect the accurate interpretation of data by the 3D printer.

Using Autodesk® Meshmixer™ 3.5.474, we created an external shell around the blood pool CT contrast acquisition, generating a wrap (3mm offset distance) surrounding the negative silhouette of the chambers and vessels (making hollow). Windows allowing intracardiac inspection were created for better visualization. A flat base was developed to maintain the structural integrity of the models during assembly and diminish supports necessity. Examples of free 3D modeling software include Autodesk® Meshmixer™ and Blender®.

Valve representation

Standard echocardiographic devices do not allow free export of data in a format eligible for printing and require specific proprietary software packages, challenging the representation of cardiac valves in affordable CHD models.⁶ For CHD models in which the representation of the valve apparatus was essential, such as AVSD and *Truncus arteriosus*, cardiac valves were digitized separately from two-dimensional echocardiography.

The heightmap technique is a cartographic strategy that has been used to create 3D maps (with depth and height) from 2D satellite/aerial views. It interprets the distance of displacement (or “height”) according to different luminosity degrees in parts of an image. They are usually displayed as a gray scale, where black represents minimum height (low areas) while white represents higher areas with a range of intensity luminosities/heights in between.

2D grayscale JPG echo images of AVSD (end-systolic subcostal view of the common AV valve) and *Truncus Arteriosus* (parasternal short axis end-diastolic view of the truncal valve) were selected. The acquired 2D grayscale pixel matrix (x,y cartesian axes data) from the echo was converted to STL format using the Heightmap technique in the online tool Fabconvert®. After that, valves were graphically modelled, volume boosted, and design improved (Autodesk® Meshmixer™ 3.5.474) and digitally inserted into the prototypes (Figure 1).

Slicing

The finalized digital models (STL or OBJ files) were converted into programming commands by PrusaSlicer® 2.4.2. Slicers segment the model into numerous layers, allow the addition of key printing parameters, and translate 3D data into G-code graphic representation extension, which contains commands that enable the printer to execute the physical manufacturing process. Examples of free slicers include PrusaSlicer®, Cura®, Craftware®, Repetier®, and Slic3r®.

3D printing technical parameters

Filament type *polylactic acid* (PLA) 1.75mm, 1.24g/cm³, nozzle temperature 210°C first layer (205°C subsequent), bed temperature 60°C, maximal volumetric speed 15mm³/s, 5mm retraction, and 60mm/s speed retraction. Printing nozzle diameter 0.4mm, resolution layer height 0.24mm, first layer (0.2mm subsequent), infill 20%, infill pattern hexagonal, top-bottom thickness 3mm, perimeter/bridges/support/infill speed 60mm/s, first layer 20mm/s, and skin overlap percentage 25%. Special modes, “adaptive layers,” and “smoothness” were used.

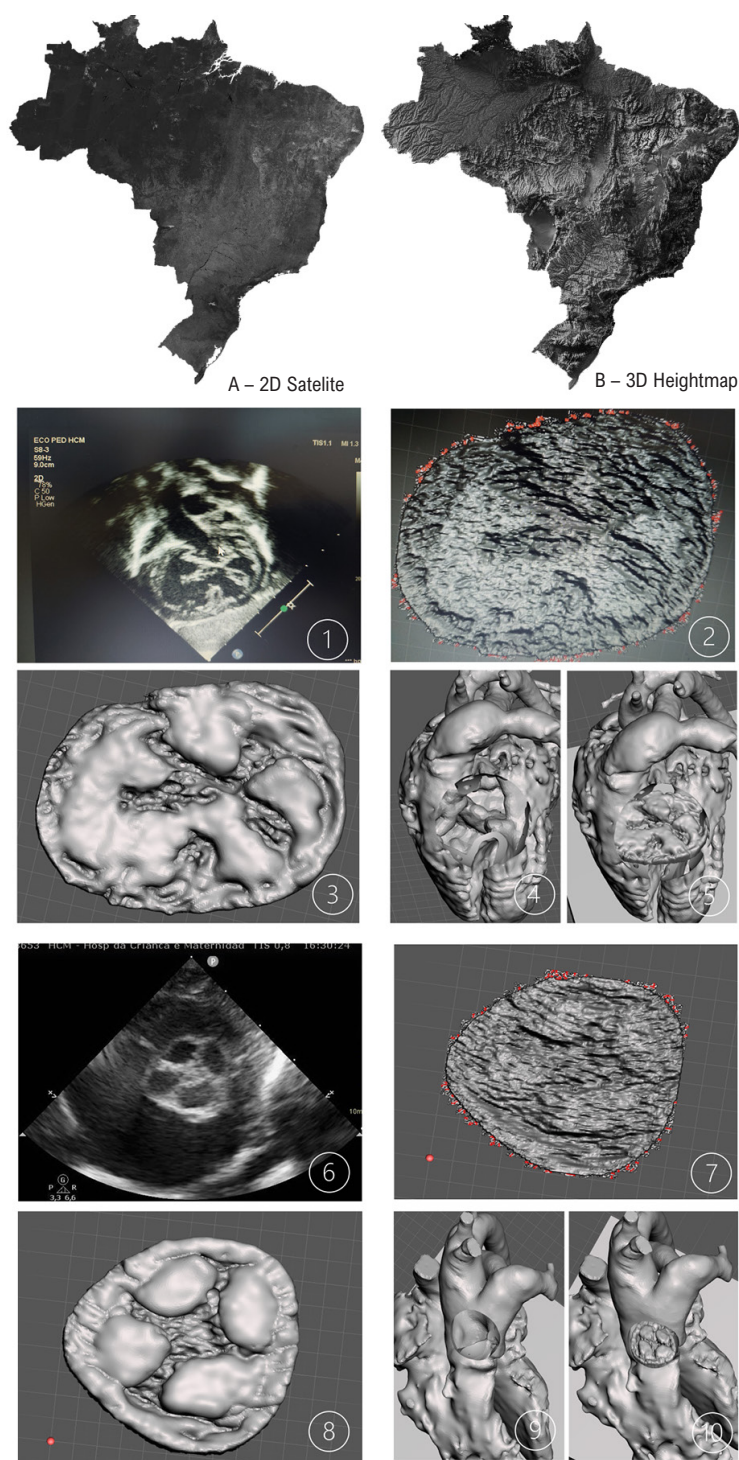


Figure 1 – Use of cartographic heightmap technique for conversion of 2D satellite images into 3D volume/height boosted maps as an alternative strategy for 3D modeling cardiac valves for educational purposes from a single 2D echocardiography (ECHO) image sample. A: 2D Brazil satellite 2D-image; B: Brazil heightmap; 1: ECHO image of a common atrioventricular valve end-systolic subcostal view in .jpg format; 2: Volumetric effect after Heightmap technique processing in .stl format; 3: Digital design volume boost optimization; 4 and 5: Insertion of final 3D object inside atrioventricular septal defect 3D frame; 6-10: Same process applied for a quadricuspid truncal valve end-diastolic parasternal short axis view ECHO image sample for 3D modelling of truncus arteriosus educational model.

It is essential to thoroughly know your machine's specifications and settings to optimize a low-cost desktop 3D printer by tuning key process parameters⁷.

3D printer features

CHD educational models were developed by the Fused Deposition Modeling (FDM) additive manufacturing process technique in a Creality® Ender 3™ domestic monofilament 3D printer with white PLA National 3D® PLA MAX™ 1.75mm filament.

Post printing

Removal of thermoplastic residues and finishing of the model.

Initial CHD prototypes

Twelve 3DP prototypes have been developed representing the following CHDs and subtypes: 1) Perimembranous central VSD with PDA; 2) *Ostium secundum* ASD; 3) TOF with pulmonary stenosis; 4) TGA; 5) Total AVSD type A (Rastelli classification); 6) CoA; 7) HLHS; 8) TriAtr type IC; 9) PulAtr type A (Barbero-Marcial classification); 10) TAPVC infracardiac type; 11) *Truncus arteriosus* type 1 (Collett-Edwards classification); and 12) IAA type C (Celoria-Patton classification).

Expert team composition and initial evaluation of 3D-Printed CHD prototypes

Composed of 26 physicians affiliated with CardioPedBrasil® from various specialties, including pediatric cardiology, pediatric echocardiography, pediatric intensive care, pediatric cardiovascular radiology, pediatric interventional cardiology, and pediatric cardiovascular surgery.

They were briefed on the twelve 3DP CHD initial prototypes and completed a structured Likert-type questionnaire (QuestionPro Survey Software®). Data were analyzed, and the models were enhanced to optimize educational experience.

Final models and creation of an educational box set

Following expert recommendations, the final models were standardized and 10% oversized compared to the original prototypes (Figures 2 to 6). The models were packaged in hardwood boxes with internal compartments and informative plates identifying each prototype.

Clinical application scenario (educational session)

Fifteen cardiology and cardiac surgery residents were invited to a 3-hour seminar contemplating the main aspects of each of the 12 CHD proposed models. They attended a traditional educational session with audiovisual equipment (teaching with slides on a screen) and were exposed to the 3DP CHD educational box set (enhanced final version). A new qualitative assessment was performed.

Financial issues

Financial planning is essential for a sustainable CHD 3D printing initiative. Infrastructure, facilities, equipment,

maintenance, and funding are vital concerns. Software licenses, high-performance printers, and realistic printing supplies can be very expensive. Costs with support staff's working hours as pediatric cardiac radiologist, biomedical engineering, digital designer, and all human resources integrated into the chain process vary in each country and need to be considered⁸. The use of free software, desktop 3D printers (some from under US\$300 - 2025), and low-cost filaments (PLA 10-40 US\$ per kilogram - 2025) enables prototyping with reduced expenditure. With self-goal-oriented study of printing steps and software functioning (segmentation, digital design, and slicing), professional working hours costs can be dramatically diminished, and any researcher can develop their own set of prototypes.

Results

All residents strongly agreed with the statement: "I consider difficulty in spatial visualization one of the main obstacles to understanding congenital heart diseases". Eighty percent of them had no previous knowledge about medical 3D printing.

Evaluating each model individually, 100% of residents strongly agreed that they were able to identify the primary anatomical characteristics defining VSD + PDA, ASD, TGA, CoA, HLHS, PulmAtr, TAPVC, *Truncus Arteriosus*, and IAA; other models' evaluation (strongly agree/agree/disagree/strongly disagree) were ToF (86.6%/13.3%/0%/0%), AVSD (73.3%/26.6%/0%/0%), and TricAtr (86.6%/13.3%/0%/0%). Analysis of the main features related to the set of models is expressed in Figure 7.

They identified as potential educational benefited groups for 3DP CHD models "undergraduate students" (100%), "interdisciplinary team" (100%), "cardiologists, cardiac surgeons and residents" (100%); and "family and children's caregivers" (93%) (Figure 8).

Discussion

This is a Brazilian initiative to develop a set of 3DP CHD models, based on real patient cases, potentially useful as a tool for pediatric cardiology and cardiac surgery education. We intend to describe a low-cost workflow, methodologically reproducible for any researcher, professional, or student using free software that's easily available for downloading. There are online free courses aimed at teaching how to work with segmentation, digital design, slicing, and 3D printer technology. The original research with full detailing and all 3DP CHD models created are available for free at <http://sites.google.com/view/3dpequenoscoracoes> and <http://cardiopedbrasil.com.br/pesquisa> as STL files for 3D printing. We expect that everyone can print their own set of 3D models and apply them in your realities to share knowledge. In Brazil, examples in the field of 3D printing, CHD, and education were published, highlighting the increasing importance of this topic.⁷⁻¹¹ Education is, and always must be, the main goal of efforts to qualify all people dedicated to children with CHD.

Traditional teaching methods, regardless of the educational resource used, are limited to flat-surface representations of



Figure 2 – Representative 3D-printed congenital heart disease (CHD) models. 1: Proposal for an educational box of 3D-printed CHD models; 2: Model of ostium secundum atrial septal defect (ASD); 3 and 4: Model of perimembranous central ventricular septal defect (VSD) with Patent Ductus Arteriosus (PDA).

anatomy. Whether it is textbooks, diagrams, radiographs, echocardiography, catheterizations, or projections of volumetric renderings from CT or magnetic resonance imaging exams, when presented on a screen or monitor, all ultimately represent the heart in two planes.¹²

Although dissection and study of pathological specimens have historically remained the gold standard of anatomical education, there are limitations to maintaining this practice.¹³ In fact, in most healthcare facilities worldwide, direct observation of specimens during surgical procedures, autopsies, or within pathology laboratories is either limited or not available. Iwanaga et al., reviewing modern methods of anatomy education, highlighted the importance of a multidisciplinary approach, including 3D printing, augmented reality, and virtual reality. They related that learning through 3DP is generally perceived to be enjoyable and effective.¹⁴

3D printing is a rapid manufacturing method used to create physical, three-dimensional objects from digital files. Recent technological advancements and the expiration of industrial patents have significantly reduced the costs of 3D printing equipment and supplies, making this technology more accessible. Thus, cost-effective approaches have been explored. Gómez-Ciriza et al. developed CHD models using free software, desktop 3D printers, and low-cost materials, maintaining great anatomical accuracy and high quality suitable for clinical practice.¹⁵ Sun et al. showed that low-cost 3DP CHD models were highly accurate in replicating anatomy, highlighting the feasibility of 3DP technology in medical education and clinical practice.¹⁶ Grieshaber et al. described a workflow based exclusively on the use of open-source software and low-cost hardware suitable for regions with low economic resources.¹⁷

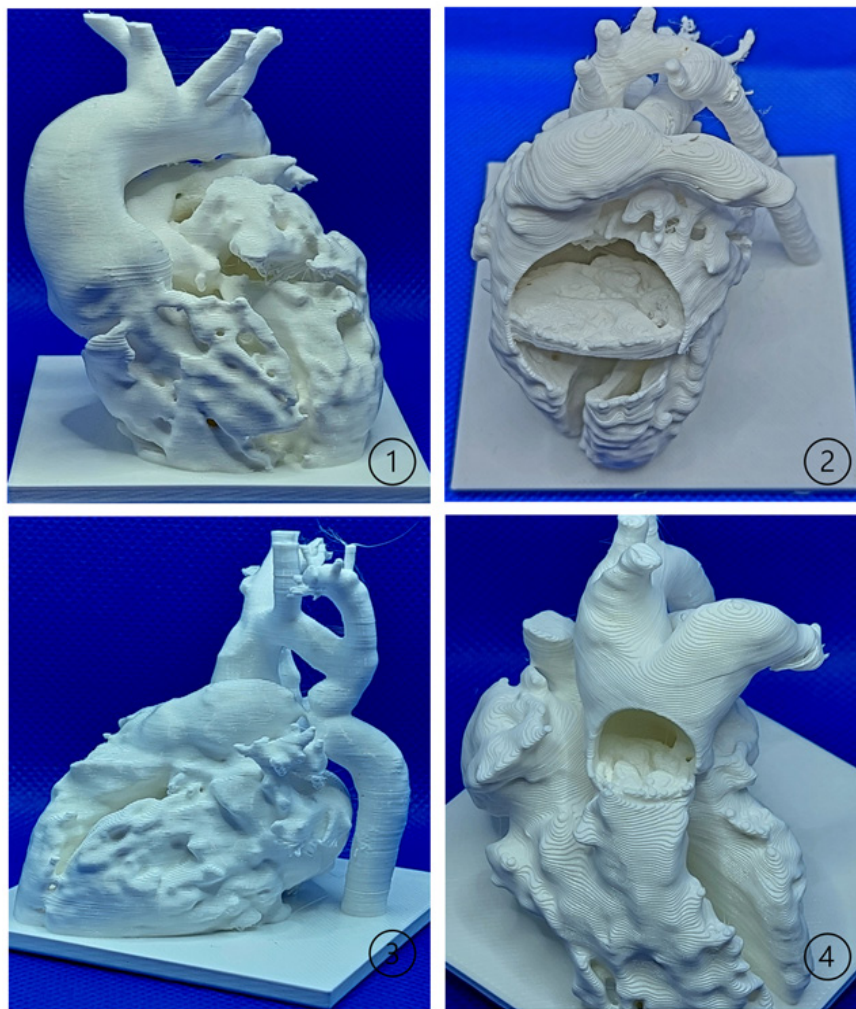


Figure 3 – Representative 3D-printed congenital heart disease (CHD) models. 1: Transposition of the Great Arteries (TGA) model; 2: Total atrioventricular septal defect (AVSD) type A (Rastelli classification) model; 3: Coarctation of the Aorta (CoA) model; 4: Truncus arteriosus type 1 (Collett-Edwards classification) model.

The quality of 3D models is influenced by characteristics of each imaging modality. In this study, educational 3DP models were developed based on cardiac CTAs known for their excellent visualization of vascular structures. Consequently, the 3DP models that predominantly characterize extracardiac defects, such as TGA, CoA, HLHS, TAPVC, IAA, PulmAtr, and *Truncus arteriosus*, received higher evaluations from evaluators compared to prototypes representing intracardiac defects like TOF, AVSD, and TricAtr.

Many factors can affect the dimensional accuracy of 3DP anatomical structures, including the quality of image acquisition, segmentation, digital design, slicing parameter configuration, 3D printer resolution, and type of filament.¹⁸ The anatomical accuracy of 3DP models was studied by Lee, Squelch, and Sun, who compared the 3DP models to original CT images of congenital defects. After analyzing multiple

anatomical landmarks, the authors related an excellent anatomical correlation ($r = 0.99$) and minimal differences between the 3DP models and original images, all measuring less than 0.5 millimeters (mean = 0.21 ± 0.37 mm; mean percentage difference ranging between 0.4 and 0.9%), with no statistically significant difference.¹⁹ In our study, 93.3% of cardiology and cardiac surgery residents 93.3% strongly agreed that 3DP CHD models were “faithful to the anatomy of the disease”, “visually appealing”, and “of adequate size”.

High-quality imaging is essential for the prototyping process. However, CT is not always the necessary complementary exam for diagnosing and managing certain CHDs. In this context, to develop some of the 3DP models presented in this study, we sought image sets of CHD patients who had undergone a cardiac CT to investigate associated morbidities. Example: an infant diagnosed with a VSD and obstructive respiratory

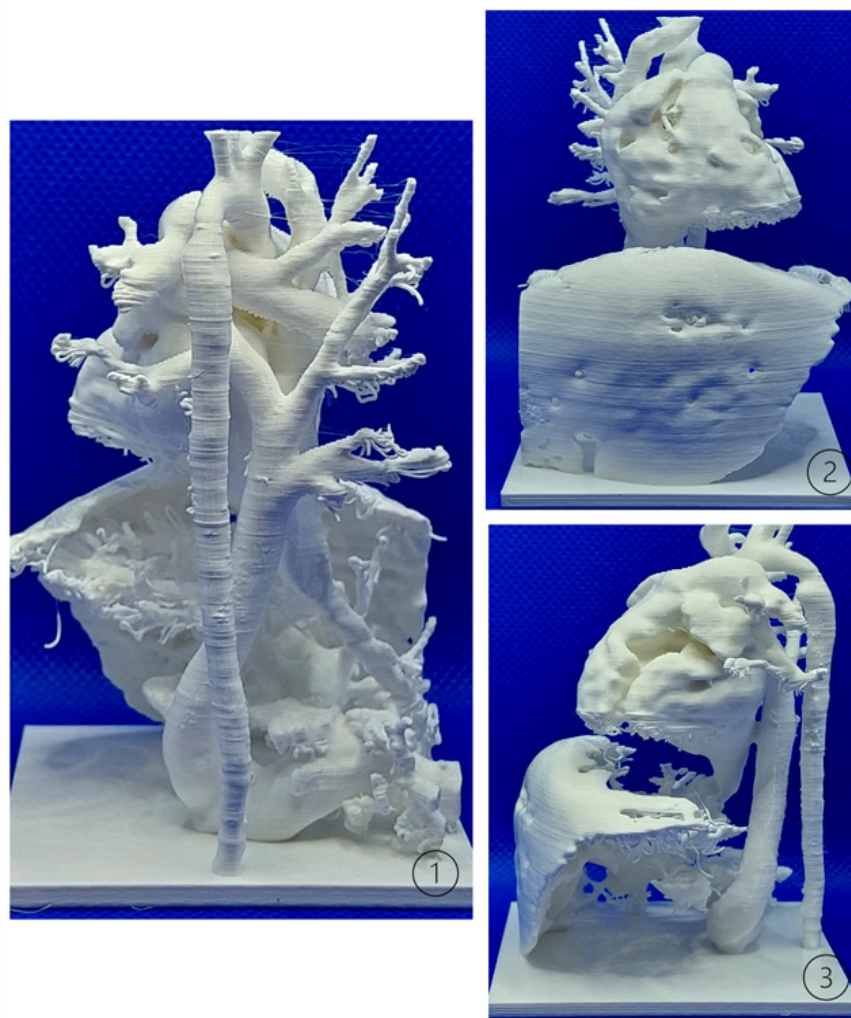


Figure 4 – Representative 3D-printed model of Total Anomalous Pulmonary Venous Connection (TAPVC) infracardiac type. 1: Wide view; 2 and 3: Detailed views.

symptoms, who underwent a CT to investigate extrinsic airway compression. This strategy made it possible to find images of ASD, ToF, AVSD, and TGA. The selected images were processed to eliminate irrelevant details, emphasizing only the lesions of educational interest.

Cardiac valves and support apparatuses are important anatomic landmarks of cardiac morphology. Valve leaflets and chords are constantly moving, delicate structures, and accurate 3D replication remains challenging, especially when developing affordable CHD 3DP models. Echocardiography offers superior visualization of valve apparatus, but the absence of standardized format storage and difficulties in converting files to DICOM are limiting factors. Specialized centers can develop very realistic 3DP cardiac valves using hybrid approaches combining different imaging modalities, graphic computer-aided design tools, and soft printing materials.²⁰⁻²²

In our research, we did not have access to commercial echocardiographic software packages. Thinking about how 3D topographic maps are produced based on 2D satellite images, we used the Heightmap cartographic technique to convert 2D echo files to STL, graphically optimize them, and integrate final object valves (ring and leaflets) to the models.

Concepts in pediatric cardiology are routinely shared by a heterogeneous group, including students, residents, physicians, nurses, physiotherapists, family members, and patients. Spatial visualization ability refers to the cognitive capacity to understand and mentally manipulate conceptual objects, comprehending the relationship between objects in space. In this context, the improvement of spatial visualization ability offers educational advantages in understanding anatomy and the development of motor skills.²³ Our study revealed that for 100% of residents

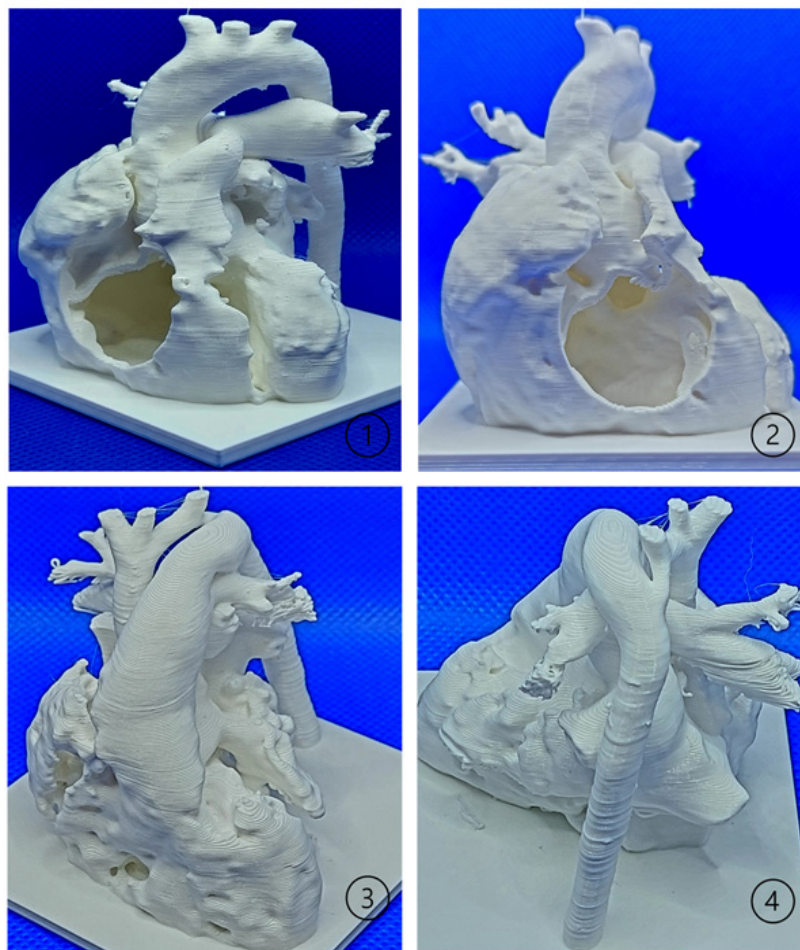


Figure 5 – Representative 3D-printed congenital heart disease (CHD) models. 1 and 2: Model of Tetralogy of Fallot (TOF) with pulmonary stenosis; 3 and 4: Hypoplastic Left Heart Syndrome (HLHS) model.

interviewed, “difficulty in spatial visualization is one of the main obstacles to understanding CHD”.

Due to the complexities of CHD anatomy, 3DP CHD models are well-suited as an adjunct to traditional teaching methods as they overcome limitations with 2D representations of 3D structures.

In a randomized clinical trial, Karsenty et al. showed the educational benefits of using 3DP CHD models for teaching. The group exposed to the models showed superior levels of objective knowledge and satisfaction compared to the control group. The possibility of sharing and manipulating 3DP models positively influenced the evaluations.²⁴ Su et al. demonstrated that 3DP models offer advantages over other pedagogical tools, as they provide rich spatial and structural information and can be optimized for educational purposes. The 3DP models were more effective than other strategies in terms of knowledge acquisition and structural conceptualization.²⁵ For the Tarca et al. cohort, the 3DP group had a significant increase in subjective confidence,

knowledge, and post-intervention examination score. 92% of participants rated 3D models as “very useful” or “useful” (average rating of 4.7/5.0).²⁶ In our context, 100% of residents’ evaluators considered that 3DP CHD models “are an important pedagogical resource”, “easy to manipulate”, “apparently resistant”, and “capable of motivating the study”.

The tactile properties of 3DP models may offer a positive evaluation of the learning experience. Lau and Sun compared medical student groups that attended a 1.5-hour-long educational session and had access to identical teaching materials (2D diagrams, 3D digital models, DICOM images). An intervention group used 3DP CHD models. They showed no statistically significant improvement in immediate and long-term (6 weeks after) CHD knowledge acquisition, but students indicated that the teaching method was “interactive and interesting”, “easy to understand”, “knowledge about CHD has improved”, and “played an important role in helping them to understand CHD”.²⁷ We

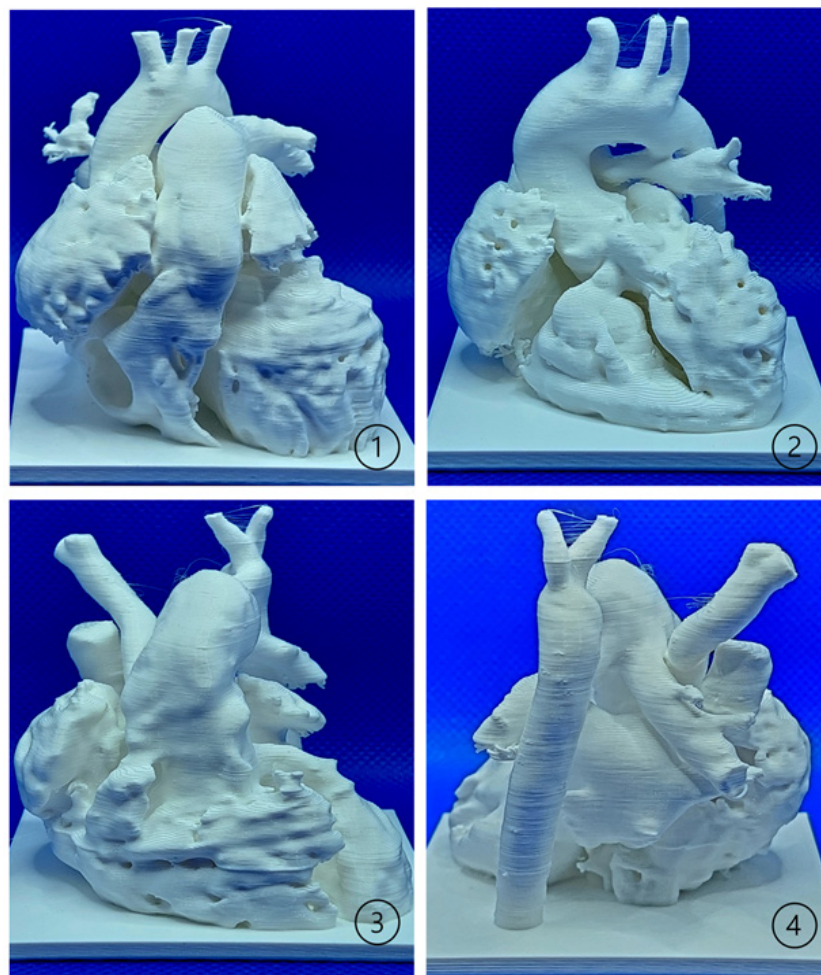


Figure 6 – Representative 3D-printed congenital heart disease (CHD) models. 1: Tricuspid atresia (TricAtr) type IC model; 2: Pulmonary Atresia (PulAtr) with ventricular septal defect type A (Barbero-Marcial classification) model; 3 and 4: Interrupted Aortic Arch (IAA) type C (Celoria-Patton classification) model.

have found a confident answer behavior since residents related 3DP CHD models “allow better spatial and structural conceptualization” and are “useful for understanding more complex heart diseases”.

Hessen et al. developed an innovative teaching program including 3D printing as a tool for anatomy education of medical students. Undergraduate medical students were trained to construct 3D models and/or extended reality prototypes. Qualitative survey questions (minimal-maximal scores 1-5) inferred that students considered the built anatomical models “draw my attention (4.4)”, were “attractively constructed (4.1)”, “easy to use (4.0)”, “stimulated me to actively engage (4.7)”, “were meaningful to work with (4.2)”, “provided satisfaction (4.1)” and “motivated me to study anatomy (4.5)”.²⁸ Similar responses were found in our residents’ evaluation.

Biglino et al. evaluated the potential of patient-specific models in improving parental understanding during consultations. Feedback analysis revealed that 3DP models were quickly comprehensible, stimulated curiosity, and could be particularly useful. The authors concluded that these models optimized communication and positively impacted psychological acceptance of treatment.²⁹ The same researchers assessed the effect of using 3DP CHD models in consultations with adolescents aged 15 to 18. A significant improvement was observed in their confidence in explaining their own condition ($p=0.008$), disease knowledge level ($p=0.005$), and satisfaction with the consultation ($p=0.005$).^{30,31}

Technological advancement has made it possible to incorporate the use of virtual reality (VR), augmented reality (AR), computational modeling, and artificial intelligence (AI) in CHD practice. These methods are allies of standard imaging

Original Article

The 3D printed CHD educational models are:

STATEMENT	Strongly Agree	Agree	Disagree	Strongly Disagree	Overall
Faithful to the anatomy of the disease	14 93.3%	1 6.6%	0 0%	0 0%	15 100%
Visually appealing	14 93.3%	1 6.6%	0 0%	0 0%	15 100%
Adequate size	14 93.3%	1 6.6%	0 0%	0 0%	15 100%
Easy to manipulate	15 100%	0 0%	0 0%	0 0%	15 100%
Apparently resistant	15 100%	0 0%	0 0%	0 0%	15 100%
Capable of motivating the study of congenital heart disease	15 100%	0 0%	0 0%	0 0%	15 100%

Used during educational session, the 3D printed CHD educational models:

STATEMENT	Strongly Agree	Agree	Disagree	Strongly Disagree	Overall
Makes me better understand congenital heart diseases	15 100%	0 0%	0 0%	0 0%	15 100%
Are an important pedagogical resource	15 100%	0 0%	0 0%	0 0%	15 100%
Increased my interest in the study of congenital heart disease	15 100%	0 0%	0 0%	0 0%	15 100%
Allow better spatial and structural conceptualization of diseases	15 100%	0 0%	0 0%	0 0%	15 100%
Useful for understanding more complex heart disease	15 100%	0 0%	0 0%	0 0%	15 100%

Figure 7 – Resident's evaluation of 3D-printed congenital heart diseases (CHD) models developed in this research (n=15).

techniques and deliver personalized medicine. Immersive visualization tools can optimize educational opportunities, communication during consultations, surgical planning, decision making, device manufacturing projects, computational fluid, and dynamic circulatory simulation. These tools similarly demand computers, VR headsets, advanced medical imaging processes, and proper expertise. Although static, 3D printing offers tactile properties and a long-term physical collection of pieces in a scenario of scarcity of pathological CHD specimens. Tissue engineering is an emerging field seeking the promise of 3D bioprinting vascular scaffolds, valves, heart, tissue patches, myocardium and ultimately beating hearts³¹.

Limitations and future perspectives

Prototypes were manufactured using a desktop 3D printer equipped with a single extruder nozzle, allowing for the use of only one type of filament and color at a time.

PLA filament was chosen because it is easily accessible, low-cost, and it's capable of generating models with satisfactory physical features for educational purposes.

Cardiac valves were represented using an alternative, non-validated approach. We accepted this raw representation (just ring and leaflets) because the models were solely intended for educational purposes. However, it would not be suitable if we aimed for clinical decision-making or surgical planning, where precise anatomical replication of papillary muscles and chordae tendineae is essential.

By the intrinsic characteristics of medical residency, this group of evaluators had a close relation to the main researcher, which may influence the way the set of 3D models was analyzed. However, the expert team evaluation has shown convergent responses that make us believe in the coherence of residents' answers.

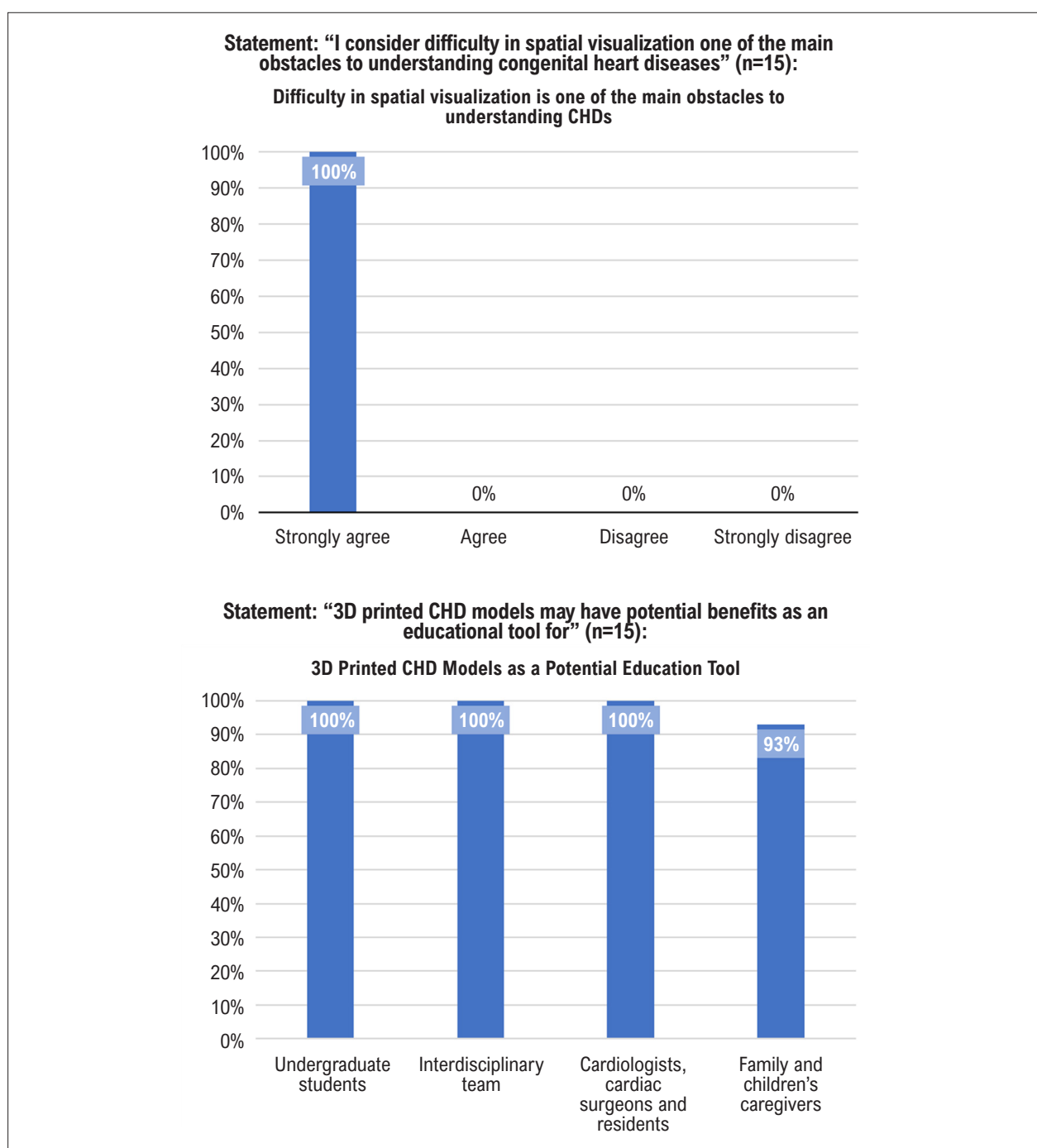


Figure 8 – The resident's answers were based on the presented statements. (n=15).

Transdisciplinary work was fundamental for this project. Technical expertise obtained will pave the way for an expanded educational box, which may include diseases not explored here.

Conclusion

Development of 3DP CHD models using a low-cost workflow is feasible. We suggested a detailed process

with open-source, freely available software, an alternative strategy for cardiac valve representation, low-cost materials, and a desktop 3D printer that can be reproduced by any researcher in low-resource settings. Models developed are freely available for download at <http://sites.google.com/view/3dpequenoscoracoes> and <http://cardiopedbrasil.com.br/pesquisa>.

Author Contributions

Conception and design of the research: Cajueiro FCM, Croti UA, Amorim Júnior RF, Godoy MF; Acquisition of data: Cajueiro FCM, Croti UA, Cardoso MRR, Costa CH, De Marchi CH; Analysis and interpretation of the data: Cajueiro FCM, Croti UA, Amorim Júnior RF, Costa CH, Godoy MF; Statistical analysis: Cajueiro FCM, Croti UA, Godoy MF; Obtaining financing and Writing of the manuscript: Cajueiro FCM; Critical revision of the manuscript for content: Cajueiro FCM, Croti UA, De Marchi CH, Borim BC, Godoy MF, Freitas MB, Moscardini AC.

Potential conflict of interest

No potential conflict of interest relevant to this article was reported.

Sources of funding

There were no external funding sources for this study.

Study association

This article is part of the thesis of doctoral submitted by Francisco Candido Monteiro Cajueiro, from Programa de Pós-graduação em Ciências da Saúde da Faculdade de Medicina de São José do Rio Preto (FUNFARME/FAMERP).

Ethics approval and consent to participate

This study was approved by the Ethics Committee of the Faculdade de Medicina de São José do Rio Preto under the protocol number CAAE: 48575021.3.0000.5415. Informed consent was obtained from all participants included in the study.

Use of Artificial Intelligence

The authors did not use any artificial intelligence tools in the development of this work.

Data Availability Statement

The underlying content of the research text is contained within the manuscript.

References

- Langlois J, Bellemare C, Toulouse J, Wells GA. Spatial Abilities and Anatomy Knowledge Assessment: A Systematic Review. *Anat Sci Educ*. 2017;10(3):235-41. doi: 10.1002/ase.1655.
- Yoo SJ, Hussein N, Peel B, Coles J, van Arsdell GS, Honjo O, et al. 3D Modeling and Printing in Congenital Heart Surgery: Entering the Stage of Maturation. *Front Pediatr*. 2021;9:621672. doi: 10.3389/fped.2021.621672.
- Perens G, Chyu J, McHenry K, Yoshida T, Finn JP. Three-Dimensional Congenital Heart Models Created with Free Software and a Desktop Printer: Assessment of Accuracy, Technical Aspects, and Clinical Use. *World J Pediatr Congenit Heart Surg*. 2020;11(6):797-801. doi: 10.1177/2150135120952072.
- Liu Y, Chen S, Zühlke L, Black GC, Choy MK, Li N, et al. Global Birth Prevalence of Congenital Heart Defects 1970-2017: Updated Systematic Review and Meta-Analysis of 260 Studies. *Int J Epidemiol*. 2019;48(2):455-63. doi: 10.1093/ije/dyz009.
- Chepelev L, Wake N, Ryan J, Althobaity W, Gupta A, Arribas E, et al. Radiological Society of North America (RSNA) 3D Printing Special Interest Group (SIG): Guidelines for Medical 3D Printing and Appropriateness for Clinical Scenarios. *3D Print Med*. 2018;4(1):11. doi: 10.1186/s41205-018-0030-y.
- Hosny A, Shen T, Kuo AS, Long D, Andrawes MN, Dilley JD. Unlocking Vendor-Specific Tags: Three-Dimensional Printing of Echocardiographic Data Sets. *J Thorac Cardiovasc Surg*. 2018;155(1):143-5.e1. doi: 10.1016/j.jtcvs.2017.08.064.
- Antreas K, Piromalis D. Employing a Low-Cost Desktop 3D Printer: Challenges, and How to Overcome Them by Tuning Key Process Parameters. *Int J Mech Appl*. 2021;10(1):11-9. doi: 10.5923/j.mechanics.20211001.02.
- Bastawrous S, Wu L, Liacouras PC, Levin DB, Ahmed MT, Strzelecki B, et al. Establishing 3D Printing at the Point of Care: Basic Principles and Tools for Success. *Radiographics*. 2022;42(2):451-68. doi: 10.1148/rq.210113.
- Basso ML, Gebran AM, Oliveira JD, Gebran KM, Bonatto LC, Farah MCK. Three-Dimensional-Printed Heart Prototype for Application in Pediatric Cardiology: An Initial Experiment. *Arq Bras Cardiol*. 2021;116(3):507-9. doi: 10.36660/abc.20200086.
- Freitas MB, Figueiredo JL, Cajueiro FC, Lima RM, Freitas MH, Teixeira CM. Three-Dimensional Model Printing in Congenital Heart Disease. *Arq Bras Cardiol: Imagem Cardiovasc*. 2023;36(4):e20230065. doi: 10.36660/abcimg.20230065.
- Montanhesi PK, Coelho G, Curcio SAF, Poffo R. Three-Dimensional Printing in Minimally Invasive Cardiac Surgery: Optimizing Surgical Planning and Education with Life-Like Models. *Braz J Cardiovasc Surg*. 2022;37(1):110-17. doi: 10.21470/1678-9741-2020-0409.
- Smerling J, Marboe CC, Lefkowitz JH, Pavlicova M, Bacha E, Einstein AJ, et al. Utility of 3D Printed Cardiac Models for Medical Student Education in Congenital Heart Disease: Across a Spectrum of Disease Severity. *Pediatr Cardiol*. 2019;40(6):1258-65. doi: 10.1007/s00246-019-02146-8.
- Ghosh SK. Cadaveric Dissection as an Educational Tool for Anatomical Sciences in the 21st Century. *Anat Sci Educ*. 2017;10(3):286-99. doi: 10.1002/ase.1649.
- Iwanaga J, Loukas M, Dumont AS, Tubbs RS. A Review of Anatomy Education during and after the COVID-19 Pandemic: Revisiting Traditional and Modern Methods to Achieve Future Innovation. *Clin Anat*. 2021;34(1):108-14. doi: 10.1002/ca.23655.
- Gómez-Ciriza G, Gómez-Cía T, Rivas-González JA, Forte MNV, Valverde I. Affordable Three-Dimensional Printed Heart Models. *Front Cardiovasc Med*. 2021;8:642011. doi: 10.3389/fcvm.2021.642011.
- Sun Z. Patient-Specific 3D-Printed Models in Pediatric Congenital Heart Disease. *Children*. 2023;10(2):319. doi: 10.3390/children10020319.
- Grieshaber P, Schneller A, Fonseca-Escalante E, Farag M, Krey R, Czundel A, et al. A Low-Cost Workflow to Generate Virtual and Physical Three-Dimensional Models of Cardiac Structures. *World J Pediatr Congenit Heart Surg*. 2025;16(1):107-13. doi: 10.1177/21501351241293305.
- Wijnen N, Brouwers L, Jebbink EG, Heyligers JMM, Bemelman M. Comparison of Segmentation Software Packages for in-Hospital 3D Print Workflow. *J Med Imaging*. 2021;8(3):034004. doi: 10.1117/1.JMI.8.3.034004.
- Lee S, Squelch A, Sun Z. Quantitative Assessment of 3D Printed Model Accuracy in Delineating Congenital Heart Disease. *Biomolecules*. 2021;11(2):270. doi: 10.3390/biom11020270.

20. Tuncay V, van Ooijen PMA. 3D Printing for Heart Valve Disease: A Systematic Review. *Eur Radiol Exp*. 2019;3(1):9. doi: 10.1186/s41747-018-0083-0.
21. Bulbul Z, El Rassi I, Hamade R, Tamim H, Bitar F. Three-Dimensional Printing of Mitral Valve Models Using Echocardiographic Data Improves the Knowledge of Cardiology Fellow Physicians in Training. *Front Cardiovasc Med*. 2023;10:1307994. doi: 10.3389/fcvm.2023.1307994.
22. Gomez A, Gomez G, Simpson J, Valverde I. 3D Hybrid Printed Models in Complex Congenital Heart Disease: 3D Echocardiography and Cardiovascular Magnetic Resonance Imaging Fusion. *Eur Heart J*. 2020;41(43):4214. doi: 10.1093/eurheartj/ehaa654.
23. Gonzales RA, Ferns G, Vorstenbosch MATM, Smith CF. Does Spatial Awareness Training Affect Anatomy Learning in Medical Students? *Anat Sci Educ*. 2020;13(6):707-20. doi: 10.1002/ase.1949.
24. Karsenty C, Guitarte A, Dulac Y, Briot J, Hascoet S, Vincent R, et al. The Usefulness of 3D Printed Heart Models for Medical Student Education in Congenital Heart Disease. *BMC Med Educ*. 2021;21(1):480. doi: 10.1186/s12909-021-02917-z.
25. Su W, Xiao Y, He S, Huang P, Deng X. Three-Dimensional Printing Models in Congenital Heart Disease Education for Medical Students: A Controlled Comparative Study. *BMC Med Educ*. 2018;18(1):178. doi: 10.1186/s12909-018-1293-0.
26. Tarca A, Woo N, Bain S, Crouchley D, McNulty E, Yim D. 3D Printed Cardiac Models as an Adjunct to Traditional Teaching of Anatomy in Congenital Heart Disease-A Randomised Controlled Study. *Heart Lung Circ*. 2023;32(12):1443-50. doi: 10.1016/j.hlc.2023.09.021.
27. Lau I, Sun Z. The Role of 3D Printed Heart Models in Immediate and Long-Term Knowledge Acquisition in Medical Education. *Rev Cardiovasc Med*. 2022;23(1):22. doi: 10.31083/j.rcm2301022.
28. Henssen D, Karstens J, De Jong G, Duits JD, Boer L, Brink M, et al. Implementing 3D Printing and Extended Reality in Anatomy Education: Organization, Evolution, and Assessment of an Innovative Teaching Program in an Undergraduate Medical School in the Netherlands. *Ann Anat*. 2025;257:152354. doi: 10.1016/j.aanat.2024.152354.
29. Biglino G, Capelli C, Wray J, Schievano S, Leaver LK, Khambadkone S, et al. 3D-Manufactured Patient-Specific Models of Congenital Heart Defects for Communication in Clinical Practice: Feasibility and Acceptability. *BMJ Open*. 2015;5(4):e007165. doi: 10.1136/bmjopen-2014-007165.
30. Biglino G, Koniordou D, Gasparini M, Capelli C, Leaver LK, Khambadkone S, et al. Piloting the Use of Patient-Specific Cardiac Models as a Novel Tool to Facilitate Communication during Clinical Consultations. *Pediatr Cardiol*. 2017;38(4):813-8. doi: 10.1007/s00246-017-1586-9.
31. Chessa M, Van De Bruaene A, Farooqi K, Valverde I, Jung C, Votta E, et al. Three-Dimensional Printing, Holograms, Computational Modelling, and Artificial Intelligence for Adult Congenital Heart Disease Care: An Exciting Future. *Eur Heart J*. 2022;43(28):2672-84. doi: 10.1093/eurheartj/ehac266.

