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The Usefulness of 3D Heart Models as a Tool of Congenital Heart Disease Education: A Narrative Review

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Abstract

Objectives: **The objective of this review is to evaluate the effectiveness of three-dimensional (3D) heart models as teaching tools for congenital heart disease (CHD), addressing the limitations of traditional medical education methods.**

Methods: **A thorough literature review was conducted using PubMed, Google Scholar, Scientific Direct and Scopus databases. Relevant articles were screened and selected based on their discussion of the application of 3D models in CHD education.**

Results: **The comprehensive review of 19 studies revealed that 3D heart models provide students, healthcare professionals, and patients with meaningful experiences that significantly enhance understanding and learning outcomes. These models improve objective knowledge, structural conceptualization, and personal satisfaction in medical education, especially in complex CHD compared to traditional methods such as books and 2D images ($p < 0.001$). Additionally, they enhance spatial orientation, surgical planning, simulation training, clinical reasoning, and critical thinking of healthcare providers. Patients and parents showed better comprehension and confidence in explaining their condition to others. Despite the cost and technical limitations, 3D models of CHD show promising potential.**

Conclusion: **Integrating 3D heart models into CHD education has positively impacted knowledge acquisition, satisfaction, and confidence across various learner populations. The interactive and tangible nature of 3D models offers advantages over traditional teaching methods, fostering a deeper understanding of complex cardiac structures and pathology. However, further research is necessary to investigate long-term benefits and develop effective integration strategies in medical curricula and practice.**

Keywords: Congenital heart disease, 3D models, Medical education, Three-dimensional heart printing, Healthcare providers

1. Introduction

Approximately 1 % of live births worldwide are affected by congenital heart disorders (CHDs), the most prevalent kind of birth defect. Advances in treatments and control of chronic degenerative and congenital diseases have extended the lifespan of affected individuals. For congenital cardiac malformations, about 10 out of 1000 newborns have some anomaly, with one-third requiring surgical intervention [1]. Early diagnosis and improved surgical techniques have increased the number of children and adolescents living with heart disease [2].

Medical education utilizes traditional methods including books, two-dimensional illustrations (2D), cadaver dissections, and radiological images but these methods do not entirely engage learners and bridge the gap between knowledge and application. Innovative instructional approaches like three-

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dimensional (3D) heart models are essential to improve comprehension and understanding of CHDs, as demonstrated in Fig. 1 [3,4].

It is confirmed that most of the students prefer tactile learning (i.g. kinaesthetic learning) and as 3D printed models offer physical interactions, they are essential in training medical professionals [5]. Physical interaction during learning is the key to gaining motor skills needed for surgical intervention, thereby improving the patient outcomes [6]. Compared to cadaveric materials, using 3D prints does not put students at a disadvantage; in fact, the results generally indicate that 3D may improve anatomy education and encourage its usage as an adjunct to cadaver-based curricula [7].

An inventive way to supply instructional materials for undergraduate anatomy courses is through 3D printing. Few studies outside of surgical simulation and veterinary models have examined the effectiveness of 3D models in an educational setting, despite the importance and desire for accurate, useful, and realistic supplements to cadaveric material. Recent disagreements over the effectiveness of cadaver-based curricula highlight their potential limitations in light of rising cadaver costs, challenges in university funding, calls for educational reform, and the spread of innovative teaching methods [7].

This narrative review aims to explore the effectiveness of 3D heart models as a tool for CHD education by providing a detailed overview of current literature and examining the advantages of using 3D models. Notably, The effectiveness of 3D models in an educational context has not been extensively studied outside of surgical simulation and veterinary models [7]. This paper seeks to highlight their potential to revolutionize the teaching and learning process for medical students. The review will discuss how 3D heart models can offer a more interactive and engaging learning experience, facilitating a better understanding of complex cardiac anatomies and pathologies. It will address the current gaps in CHD education and propose how 3D models can be integrated into medical curricula to enhance educational outcomes.

2. Methods

In this narrative review, a comprehensive search of various databases was done in PubMed, Google Scholar, ScientificDirect, and Scopus, in June 2024. The search terms to streamline our search were “education”, “teaching”, “three-dimensional heart model”, “three-dimensional heart print”, “congenital heart disease” and “Congenital heart defect”. The search process commenced with a screening of titles and abstracts from the identified studies within the databases. Subsequently, articles were evaluated for their relevance and were included in this review based on the authors' expert judgment. From the initial screening, 19 articles were selected, and their full-text versions were retrieved for a more comprehensive analysis.

The review only included articles related to 3D heart models applications in CHD education that were written in the English language without a time limit. The Studies with 3D heart models but not CHD models, non-English language publications, along with unpublished works were excluded. By examining these articles, we aim to provide insights

List of abbreviations

3DPHM	3D-printed Heart Models
AR	Aortic Regurgitation
AS	Aortic Stenosis
ASD	Atrial septal defect
AVCD	Atrioventricular Canal Defect
AVSD	Atrioventricular Septal Defect
BCPS	Bidirectional Cavopulmonary Anastomosis
bAV	bicuspid Aortic Valve
BVF	Bulboventricular Foramen
CBL	Case-Based Learning
CoA	Coarctation of the Aorta
CT	Computed Tomography
CHD	Congenital Heart Disorder/Disease/Defect
DKS	Damus-Kaye-Stansel
DILV	Double Inlet Left Ventricle
DORV	Double-Outlet Right Ventricle
HLHC	Hypoplastic Left Heart Complex
HLHS	Hypoplastic Left Heart Syndrome
IAA	Interrupted Aortic Arch
LAI	Left Atrial Isomerism
LVOTO	Left Ventricular Outflow Tract Obstruction
LV	Left Ventricle
MAPCA	Major Aortopulmonary Collateral Artery
MS	Mitral Stenosis
MCQs	Multiple choice questions
PAPVR	Partial Anomalous Pulmonary Venous Return
PDA	Patent Ductus Arteriosus
PLSVC	Persistent Left Superior Vena Cava
PA	Pulmonary Atresia
PS	Pulmonary Stenosis
RCT	Randomized Controlled Trials
RVOTO	Right Ventricular Outflow Tract Obstruction
SAS	Subaortic Stenosis
ToF	Tetralogy of Fallot
3D	Three-dimensional
TAPVC	Totally Anomalous Pulmonary Venous Connection
TGA	Transposition of the Great Arteries
TA	Tricuspid Atresia
TR	Tricuspid Regurgitation
2D	Two-dimensional
VSD	Ventricular Septal Defect

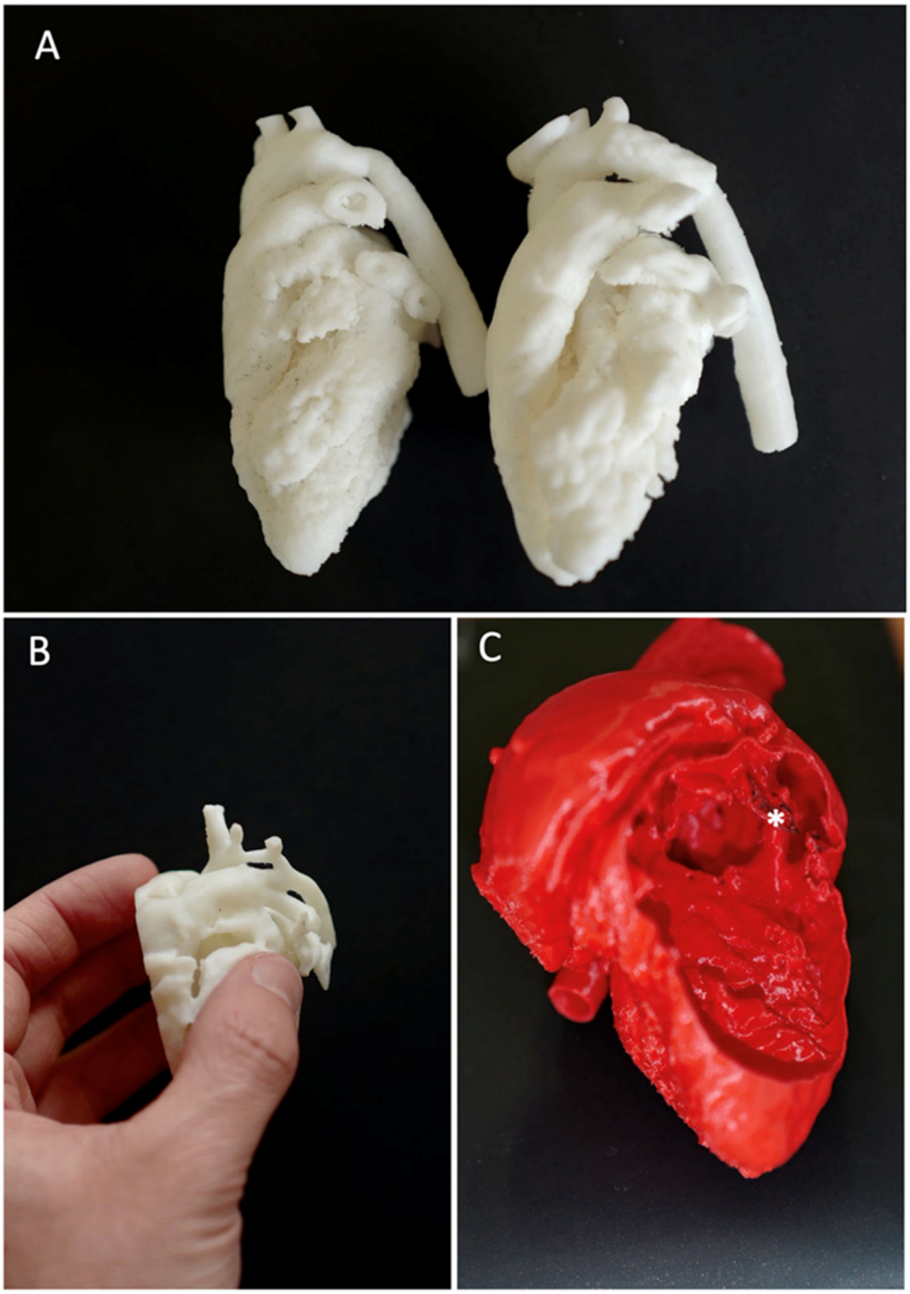

Fig. 1. By Karsenty et al. Examples of 3D-printed models. A left = isthmic aortic coarctation, right = stent-repaired of the same patient. B = neonatal aortic hypoplasia with patent ductus arteriosus. C = tetralogy of Fallot; asterisk is pointed the anterior deviation of the conal septum adapted from [9].

into how these 3D models assist in understanding and teaching CHD.

3. Results

After a meticulous search, 19 articles were selected from 2009 to 2024. Titles and abstracts of these articles were evaluated, and their full texts were retrieved. These articles encompass various aspects of CHD 3D models' use in education. Five studies involved medical students, three involved patients and parents, and eleven involved physicians, including residents, attendants, and nurses.

3.1. Medical students

In Table 1, five studies explored the application of 3D models of CHD in medical student education, two of these studies were Randomized Controlled Trials (RCT) that compared 3D models to traditional

Table 1. Overview of the studies included.

Author	Year of publication	Title	Country	Population	CHD Type	Main findings
Zhao et al. [4]	2024	Integration of case-based learning and three-dimensional printing for tetralogy of fallot instruction in clinical medical undergraduates: a Randomized controlled trial	China	60 medical students	ToF.	One group 3D model plus CBL and the other CBL alone. 3 D group showed higher scores in post class test in all subjects with total 34.300 ± 3.292 out of 40 compared to 31.030 ± 4.590 in the other group. Also, 3D group showed significant improvement in satisfaction about their knowledge
Su et al. [8]	2018	Three-dimensional printing models in congenital heart disease education for medical students: a Controlled comparative study	China	63 medical students	VSD.	Students were randomly allocated into two groups to participate in a seminar with or without 3D printing. The feedback from students in the 3D group was more positive and the results of the test (62.50 ± 19.04 vs 51.29 ± 17.55) also showed a statistically significant difference in structural conceptualization in favor of the 3D group.
Karsenty et al. [9]	2021	The usefulness of 3D-printed heart models for medical student education in congenital heart disease	France	347 fifth-year medical students	ASD, VSD, CoA, ToF.	Students were randomized into either 3D printing groups or control groups. All students had the same lecture with 2D images, but the printing groups also had 3D models. Overall, objective knowledge increased and was higher in the 3D group (16.3 ± 2.6 vs 14.8 ± 2.8 out of 20). Students were more satisfied with their understanding of CHDs in the 3D printing group (4.2 ± 0.5 vs 3.8 ± 0.4 out of 5)
Costello et al. [10]	2014	Utilizing three-dimensional printing technology to assess the feasibility of high-fidelity synthetic ventricular septal defect models for simulation in medical education	USA	29 premedical and medical students	VSD.	They reported improvement in knowledge acquisition and structural conceptualization ($p < .0001$ in both) of CHD

Smerling et al. [11]	2019	Utility of 3D-printed cardiac models for medical student education in congenital heart disease: Across a spectrum of disease severity	USA	45 first-year medical students.	ASD, CoA, ToF, PS, d-TGA, HLHS.	At the 3D station, students were given a pre- and post-intervention likert scale survey to evaluate their knowledge which showed a huge increase in knowledge for every lesion ($p < 0.001$). Also, there was a strong positive correlation between mean rise in knowledge and CHD complexity.
Costello eat al [12].	2015	Incorporating three-dimensional printing into a simulation-based congenital heart disease and critical care training curriculum for resident physicians	USA	23 pediatric resident physicians.	VSD.	Improved knowledge: Pediatric residents exhibited considerable improvement in knowledge acquisition, reporting, and structural conceptualization of VSD after the simulation-based curriculum. Improved critical care competencies Pediatric residents who used these models in a simulation-based curriculum showed improvements in their ability to describe and manage post-operative complications in patients with ventricular septal defects in the critical care setting, as well as in their knowledge acquisition ($p = 00.0082$), knowledge reporting ($p =.01$), and structural conceptualization ($p < .0001$) of ventricular septal defects.
White et al. [13]	2018	Utility of three-dimensional models in resident education on simple and complex intracardiac congenital heart defects	USA	26 pediatric and pediatric/emergency medicine residents.	VSD, ToF.	Residents were divided into intervention and control groups. 3D-printed models improve resident understanding of complex congenital heart defects like ToF, but not simpler defects like VSD since control group scored higher in post-test. Also, 3D models are more beneficial for complex lesions due to difficulty visualizing spatial relationships.

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Table 1. *(continued)*

Author	Year of publication	Title	Country	Population	CHD Type	Main findings
Loke et al. [14]	2017	Usage of 3D models of tetralogy of fallot for medical education: Impact on learning congenital heart disease	USA	35 pediatric residents rotating through an inpatient cardiology rotation.	ToF.	Comparing 2D and 3D models revealed equivalent knowledge acquisition, while residents who received instruction using 3D models expressed more satisfaction. -Learner satisfaction: The group using the 3D model scored higher ($p = 0.03$). - Self-efficacy: $p = 0.39$ indicates that there was no statistically significant difference in self-efficacy scores between the 3D model group and the other group. By raising learner satisfaction, 3D models improve ToF.
Jones eat al [15].	2017	Use of 3D models of vascular rings and slings to improve resident education	USA	36 pediatric/emergency medicine residents.	CHD especially vascular rings and sling.	They were randomized into either 3D printing groups or control groups. Subjective comfort rose in both groups following the lectures. Although the improvement percentage was not statistically different (94% vs. 79%, $p = 0.206$), the intervention group's posttest score was higher (62.2 ± 16.7%) than that of the control group (45.1 ± 12.8%, $p < 0.001$), and their score rise was marginally larger (2.6 ± 1.5 vs. 1.8 ± 1.2, $p = 0.084$).

Biglino et al. [16]	2016	Use of 3D models of congenital heart disease as an education tool for cardiac nurses	UK	100 cardiac nurses (of which 65 pediatric and 35 adult).	9 types of CHD, not specified.	Nurses found 3D models more illuminating than schematics and valued. They found 3D models helped them understand overall anatomy (86%), spatial orientation (70%), and anatomical complexity after therapy (66%). No significant difference was observed between adult and pediatric nurses. To optimize 3D models, thematic analysis highlighted the need for more explanation, labels, and color used to highlight lesion of interest. In summary, 3D patient-specific models can be beneficial for adult and pediatric cardiac nurses to understand congenital heart disease anatomy after repair.
Tarca et al. [17]	2023	3D-printed models as an adjunct to traditional teaching of anatomy in congenital heart disease.	Australia	73 (30 cardiac nurses and 43 paediatric trainees)	ASD, VSD vascular ring, PAPVR, ToF TGA and DORV.	Compared to those who only used conventional methods, those who used 3D-printed cardiac models showed a significant gain in confidence and knowledge regarding congenital heart disease. Also, compared to the control group, the intervention group's post-intervention examination results improved by a greater amount. Most participants thought the 3D models were excellent for teaching, demonstrating their value, particularly for those who learn best visually. Regardless of prior cardiology experience, improvements were seen, indicating that all learners benefit from the models. In addition, 3D models facilitate a better spatial comprehension of intricate anatomical linkages and assist overcome the constraints of 2D representations.

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Table 1. (continued)

Author	Year of publication	Title	Country	Population	CHD Type	Main findings
Awori J et al. [18]	2021	3D models improve understanding of congenital heart disease	USA	25 medical personnel (18 fellows; 2 nurses; 4 nurse practitioners and one attending) and 20 parents.	ASD, VSD, PDA, TGA, AVCD and TOF.	Both medical personnel and parents perceived digital and physical 3D models to be significantly more helpful ($p = 0.01$) for understanding congenital heart disease than traditional 2D schematics. And are also useful for educating parents about CHD without significantly impacting their clinical workflow with physical 3D-printed models being more beneficial.
Riesenkampff E et al. [19]	2009	The practical clinical value of three-dimensional models of complex congenitally malformed hearts.	Germany	2 cardiac surgeons and 4 pediatric cardiologists for 11 patients, aged from 0.8 to 27 years diagnosed with complex CHDs.	VSD, DORV, RVOTO, LVOTO, AVSD, PS, ToF, TGA, TAPVC.	Realistic 3D heart modeling provides a new means for assessing complex intracardiac anatomy. Biventricular corrective surgery was achieved in 5 patients, palliative surgery was completed in 3 patients, and a lack of suitable surgical options was confirmed in the remaining 3 patients. 3D models are expected to change current diagnostic approaches and facilitate preoperative planning.

Yıldız O et al. [20]	2021	Single-center experience with routine clinical use of 3D technologies in surgical planning for pediatric patients with complex congenital heart disease	Turkey.	Cardiac team (congenital heart surgeons, pediatric cardiologists, and radiologists) for 18 children diagnosed with complex CHDs.	DORV, PS, VSD, BCPS, RVOTO, LVOTO, TGA, PDA, DILV, BVF, DKS, LAI, PLSVC.	3DPHM can help confirm or modify the planned surgical approach, particularly when the VSD position is crucial for biventricular repair, as 3DPHM enables pediatric cardiologists to better understand the spatial relationships between the VSD and great vessels. All 18 patients successfully underwent surgeries, and there were no mortalities. The 3D patient-specific cardiac models led to a change from the initial surgical plans in 6 of 18 cases (33%), and biventricular repair was considered feasible. Moreover, the models helped to modify the planned biventricular repair in five cases, for LVOTO removal and VSD enlargement. Furthermore, 3D cardiac modeling supported the alignment of pediatric cardiologists and surgeons by increasing the strength of interdisciplinary teamwork.
Olivieri LJ et al. [21]	2016	"Just-In-time" simulation training using 3-D printed cardiac models after congenital cardiac surgery	USA	22 physicians, 38 nurses, 10 ancillary care providers and 10 patients undergoing congenital cardiac surgery.	TAPVC, As, AR, RVOTO, ToF, TGA, VSD, PS, other types of CHD.	3DPHM can be used to enhance congenital cardiac critical care via simulation training of multidisciplinary intensive care teams. The benefit of the 3D models may depend on the type of provider (e.g., nurses vs. physicians) and the complexity of the surgical case. Nurses reported greater benefits from the 3D model training compared to other clinicians.

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Table 1. (continued)

Author	Year of publication	Title	Country	Population	CHD Type	Main findings
Hoashi T et al. [22]	2018	Utility of a super-flexible three-dimensional printed heart model in congenital heart surgery	Japan	20 patients.	DORV, TGA, ToF, MAPCA, IAA, MS, hypo LV, CoA, bAV, HLHC, HLHS, TA, TR, TGA, AVSD SAS.	The 3DPHM showed utility in understanding the complex anatomy and simulating the creation of intracardiac pathways, the median cardiopulmonary bypass and aortic cross-clamp times were 345 and 114 min respectively, and there were no surgical complications. No mortality was observed during the follow-up period, and all patients except four with single ventricle underwent successful biventricular repair.
Lau I et al. [23]	2022	Clinical applications of mixed reality and 3D printing in congenital heart disease	Australia	34 clinicians.		The 3DPHM were ranked as the best modality for facilitating communication with patients. Between 3DPHM and the mixed reality models, the latter were ranked as the best modality for demonstrating complex CHD lesions, enhancing depth perception, portraying spatial relationships between cardiac structures, as a learning tool, and for facilitating pre-operative planning.
Biglino et al. [24]	2017	Piloting the use of patient-specific cardiac models as a novel tool to facilitate communication during clinical consultations	UK	20 adolescent with CHD.	ToF, TGA, CoA, PA, DORV, AS with dilated ascending aorta, and Ebstein's anomaly.	During the consultation, a 3D full heart model raised from their medical imaging data was presented to each patient. A significant increase was observed in knowledge of CHD ($p < 0.001$), confidence in explaining their condition to others ($p = 0.008$), and their satisfaction ($p = 0.005$).

Galliotto et al. [25]	2024	Enhancing parental understanding of congenital heart disease through personalized prenatal counseling with 3D-printed hearts	Italy	50 parents whose fetuses were diagnosed with CHD.	Many types of CHDs.	The study was patient-specific comparison between a group with 2D illustrations, while the other with 3D models. Survey was given to all participants which assessed their knowledge of the CHD, the scores were 16.3 ± 4.6 in 3D vs 13.5 ± 4.2 in 2D group, which showed that 3D visualization has the potential to improve parental knowledge about their child's CHD and the required surgery.

Abbreviations included: tetralogy of Fallot (ToF), ventricular septal defect (VSD), atrial septal defect (ASD), coarctation of the aorta (CoA), pulmonary stenosis (PS), transposition of the great arteries (TGA), hypoplastic left heart complex (HLHC), hypoplastic left heart syndrome (HLHS), partial anomalous pulmonary venous return (PAPVR), double-outlet right ventricle (DORV), pulmonary atresia (PA), patent ductus arteriosus (PDA), atrioventricular Canal Defect (AVCD), atrioventricular septal defect (AVSD), right ventricular outflow tract obstruction (RVOTO), left ventricular outflow tract obstruction (LVOTO), totally anomalous pulmonary venous connection (TAPVC), double inlet left ventricle (DILV), bidirectional cavopulmonary anastomosis (BCPS), bulboventricular foramen (BVF), Damus-Kaye-Stansel (DKS), left atrial isomerism (LAI), persistent left superior vena cava (PLSVC), Aortic stenosis (AS), aortic regurgitation (AR), major aortopulmonary collateral artery (MAPCA), interrupted aortic arch (IAA), mitral stenosis (MS), left ventricle (LV), hypoplastic left heart syndrome (HLHS), tricuspid atresia (TA), tricuspid regurgitation (TR), bicuspid aortic valve (bAV), subaortic stenosis (SAS).

teaching methods. Both RCTs reported improvement in student objective knowledge when using 3D models [8,9]. Su et al. randomized medical students into two groups to participate in a seminar that incorporated either 3D printing techniques or traditional methods regarding Ventricular Septal Defects (VSD). The 3D printing group achieved a higher mean score (62.50 ± 19.04 vs 51.29 ± 17.55) with statistically significant differences in structural conceptualization favoring the 3D printing group, though no significant differences were found in knowledge acquisition. Open-ended responses highlighted the advantages of 3D printing for enhancing anatomical understanding. Some students noted that cardiac structures, such as the valves, were not clearly delineated and suggested improvement [8]. Karsenty et al. recruited medical students for a 20-min lecture on four CHDs (Atrial Septal Defect (ASD), Coarctation of Aorta (CoA), Tetralogy of Fallot (ToF), and VSD). Students were randomly assigned to either 3D printing groups or control groups. All attended the same lecture with 2D images, but the 3D printing group also had access to 3D models. Both groups completed multiple-choice questions (MCQs) pre- and post-lecture, and a subjective survey after the lecture. The 3D printing group demonstrated a higher mean score for objective knowledge (16.3 ± 2.6 vs 14.8 ± 2.8 out of 20, $p < 0.0001$) and reported greater satisfaction with their understanding of CHDs (4.2 ± 0.5 vs 3.8 ± 0.4 out of 5, $p < 0.0001$) [9]. Costello et al.'s study, incorporated premedical students, in addition to medical students, into a small, hands-on teaching seminar about VSD with a 3D model. Compared to pre-seminar scores, there was a significant increase in knowledge (7.02 vs 3.22) and structural understanding (6.31 vs 2.17) ($p < 0.0001$ in both). Also, students reported the high importance of continuing using these models in their education [10]. Smerling et al. conducted a workshop featuring four instructional stations addressing six types of CHDs, utilizing embryology videos, 2D models, pathology specimens, and 3D printing. At the 3D station, students completed a pre-and post-intervention Likert scale survey, which revealed a significant improvement in knowledge ($p < 0.001$) for each cardiac lesion. Also, there was a strong positive correlation between the mean rise in knowledge and CHD complexity. 3D printed models, pathology specimens, and verbal explanations were identified as the most effective teaching methods. Students believe that these models made them more confident in explaining CHDs to others (4.23 ± 0.69) and they strongly agreed to recommend their use for future educational sessions (4.40 ± 0.69)

[11]. Additionally, Zhao et al. performed an RCT on case-based learning (CBL) with or without 3D models of the ToF, revealing that 3 D group showed higher scores in post class test in all subjects with a total 34.300 ± 3.292 out of 40 compared to 31.030 ± 4.590 in the other group and higher satisfaction from the teaching mode in the 3D model group and enhanced performance in examinations in ToF imaging data analysis ($p < 0.05$). Moreover, there was an enhancement in critical thinking and clinical reasoning abilities ($p < 0.05$). This suggests that 3D-printed models can effectively enhance CBL [4].

3.2. Health care providers

A total of six studies explored the application of 3D heart printing in physician education about CHDs, as shown in Table 1. One of these studies included nurses, while the remaining focused on residents. Costello et al. investigated the integration of 3D printing technology into a seminar for CHD and critical care, targeting pediatric resident physicians. The questionnaires distributed before and after the seminar indicated that the 3D heart printing enhanced knowledge acquisition ($p = 0.0082$), documentation ($p = 0.01$), and conceptual framework development ($p < 0.0001$) [12].

The remaining studies were RCTs comparing 3D models to traditional educational methods. For example, White et al. selected pediatric and emergency medicine residents for their study. Regardless of the target participants, all these studies demonstrated the superior effectiveness of 3D-printed models compared to traditional methods, the results showed pretest and posttest scores of the ToF intervention group. The intervention group showed no significant difference in pretest scores compared to the control group [13–15]. Biglino evaluated the tool among cardiac nurses, finding that 3D printing significantly improved their understanding of overall anatomy (86 %), spatial orientation, and anatomical complexity after treatment of CHDs (66 %). The results indicated that both adult and pediatric nurses demonstrated a high level of comprehension [16]. Furthermore, Tarca et al.'s RCT compared the effectiveness of 3D models to conventional methods involving both cardiac nurses and pediatric trainees, irrespective of their prior cardiology experience. The findings revealed that the 3D models significantly enhanced knowledge in the intervention groups (both $p < 0.001$), with greater progress in pre- and post-assessment scores observed in the intervention group 21 % improvement, as opposed to an 11 % improvement in the control group. And were highly valued by most participants [17].

According to Awori, both digital and physical 3D heart models were perceived by medical personnel and parents as significantly more helpful ($p = 0.01$) for understanding CHD compared to traditional 2D schematics. Physical 3D-Printed Heart Models (3DPHM) were considered even more useful than digital 3D models for understanding CHD [18].

3.3. Use in clinical practice

The use of 3DPHMs is fundamentally transforming patient care, research, education, and communication in clinical practice, particularly in congenital heart surgical training programs. 3DPHMs have proven to be highly accurate and have been used for strategic surgical planning, and preoperative care simulation, especially in complex CHD [19], 3D printing enables the creation of patient-specific models as shown in Fig. 2, which can aid in preoperative planning and decision-making. In a study by Yõldõz et al., these models resulted in modifications to the original surgical plans in 33 % of cases [20]. Simulation training utilizing patient-specific 3DPHM of CHDs has delivered promising outcomes, with models that mimic the flexibility and elasticity of the human myocardium, accurately replicating pathological characteristics [21]. Additionally, 3DPHMs have been shown to improve the ability of novice surgeons to perform complex biventricular repairs for CHD. No mortality or complications were observed in the study [22]. Surgeons have found these models to be extremely convenient and essential. Furthermore, 3D printing enhanced collaboration among medical teams, patients, and caregivers in CHD. Specifically, 3DPHMs have been ranked as the best modality for facilitating communication with patients and are also useful for educating parents about CHD without significantly impacting their clinical workflow [18,23].

4. Patients and their parents

Additionally, these models are utilized in patient and parental education to enhance their understanding of the condition. Biglino et al. conducted a study on adolescents with CHD, demonstrating that the use of 3DPHM in consultations improved patients' knowledge ($p < 0.001$) and satisfaction ($p = 0.005$). Patients also reported increased confidence in explaining their condition to others ($p = 0.008$) [24]. Similarly, Galliotto et al.'s RCT compared 3D visualization to 2D illustrations in parents of fetuses diagnosed with CHD. The

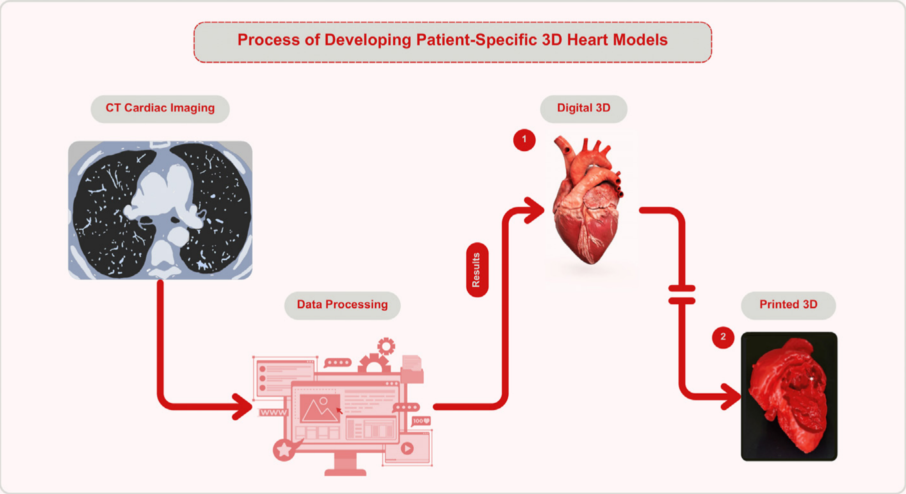

Fig. 2. By Bana shows the process of developing patient-specific 3D heart models. It begins with cardiac imaging like Computed Tomography (CT) to capture detailed images of the patient's heart. These images are then processed using specialized software to create a digital 3D model. Finally, the digital model can be used to produce a 3DPHM, which is valuable for diagnostic purposes and surgical planning.

findings indicated that 3D visualization significantly enhanced parental knowledge of their child's CHD and the necessary surgical procedures for its repair compared to 2D illustrations [25].

5. Limitations and future directions

We conducted this narrative review to compile data on the application of 3DPHM of CHD in educational settings, focusing on the exploration of their feasibility and potential utility in teaching diverse populations. However, several limitations were identified. Quantifying the clinical utility of 3D heart models is challenging, as no established metrics exist to measure their presumed diagnostic benefits or surgical procedures [19]. Most studies had small sample sizes, which may limit the generalizability of the findings, and focused exclusively on short-term knowledge acquisition [8,11,14,17,21,24,25]. Additionally, the studies were limited to a specific set of CHDs reproduced through 3D printing, which may not apply to all cases [9,15,23,24]. Data were primarily obtained through self-reported perceptions from participants [4,8−18,24]. The studies exhibited heterogeneity in terms of learner education levels, study purposes, and CHD complexity, which may have influenced the comprehension and engagement of the participants [12,13,15,17,25]. While these studies assessed acute knowledge gain, further research is needed to assess long-term retention of knowledge [9−14,17,25]. Technical limitations of 3D printing, such as high costs, production time, and accuracy issues, were also noted [8,9,20,22,25]. Nevertheless, technological advancements have begun to overcome these barriers, and future improvements may further enhance the reproduction of delicate structures like heart valves, which currently require greater refinement of accuracy [8]. Despite these limitations, 3D heart models of CHDs have the potential to positively impact the learning process of these complex defects. Further research is warranted to expand on these preliminary findings, including comprehensive studies with larger sample sizes to establish the generalizability of results, assessments of long-term knowledge retention, and exploration of the optimal use of 3D printing in teaching various cardiac anomalies. Additionally, addressing the limitations of 3D printing, such as cost, production time, and accuracy, is crucial for future advancements.

6. Conclusion

In conclusion, the integration of 3D heart models into CHD education has demonstrated a positive impact on knowledge acquisition, satisfaction, and confidence across various learner populations, including medical students, healthcare providers, and patients. Also, it enhances spatial orientation, clinical reasoning, and critical thinking of medical personnel. The interactive and tangible nature of 3D models offers a significant advantage over traditional teaching methods, fostering a deeper understanding of complex cardiac anatomy and pathology. While the existing research provides promising evidence, further investigation is necessary to assess the long-term benefits and explore effective integration strategies within medical curricula and medical practice, ensuring that 3D models reach their full potential in revolutionizing congenital heart disease education.

Ethics approval and consent to participate

Not applicable.

Availability of data and materials

All included articles are mentioned in the manuscript.

Authors' contributions

Conception and design of Study: RAA, RHMA. Literature review: RAA, RHMA, BA, MW. Acquisition of data: RAA, RHMA, BA, MW. Analysis and interpretation of data: RAA, RHMA, BA, MW. Research investigation and analysis: RAA, RHMA, BA, MW. Data collection: RAA, RHMA, BA, MW. Drafting of manuscript: RAA, RHMA, BA, MW. Revising and editing the manuscript critically for important intellectual contents: RAA, RHMA, BA, MW. Data preparation and presentation: RAA, RHMA, BA, MW. Supervision of the research: RAA, RHMA, BA, MW. Research coordination and management: RAA, RHMA, BA, MW. Funding for the research: RAA, RHMA, BA, MW.

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Conflict of interest

The authors declare that they have no competing interests.

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