Use of 3D-printed models and augmented reality in medical student education of congenital heart disease: randomized controlled trial

Tyler Langenfeld, Gabriel Bahrami, Yea-Lyn Pak, Susanne Wish-Baratz, Yuxi Zhu, Arpit Agarwal

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Table of Contents

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Abstract

Background: Three-dimensional modalities are increasingly being utilized as adjuncts for medical trainees learning about complex anatomical concepts such as congenital heart disease (CHD).

Objective: Evaluate the use of two such modalities, 3D-printed models and augmented reality (AR), in improving medical students' understanding and knowledge retention of CHD when compared to traditional teaching methods.

Methods: A prospective cohort study was performed with twenty-six first year medical students. Students were randomly assigned to receive a 30-minute teaching session using traditional slide-based lecture, 3D-printed model, or AR. Participants completed a 16-question pre-test consisting of four basic general cardiology questions and six questions each regarding the anatomy and physiology of tetralogy of Fallot and hypoplastic left heart syndrome. Participants completed a post-test immediately following the teaching session as well as a delayed post-test three weeks later.

Results: When comparing overall and subsection post-test scores, the AR group obtained perfect immediate post-test scores at a significantly increased rate compared to the lecture and 3D model groups (p=0.024). The AR group also showed significantly greater score improvement from pre- to post-test as well as notable trends suggesting increased retention in those who used the modality. Subjectively, participants in the lecture group endorsed difficulty grasping anatomy and physiology using only 2D diagrams while those in the 3D-printed model and AR groups nearly unanimously described the ability to better visualize the complex cardiac defects as an aid to their understanding.

Conclusions: Due to the visuospatial benefits of these modalities, there is potential for use in medical education to improve students' knowledge of complex anatomical and physiological concepts. Augmented reality shows encouraging trends towards improving immediate understanding and retention of complex congenital cardiac defects.

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Introduction

Determining the best methods of content delivery has become a hallmark of education research in recent years. Aligning teaching methods with students' preferred "learning styles," such as through VARK assessment, is popular among educators, though it has not been shown to improve learning.[1-2] The use of "flipped classrooms" is also growing in popularity with some estimates showing over half of U.S colleges utilize this model.[3] However, it has failed to show empirical evidence that it improves learning.[4] The primary aim across these approaches is to foster active learning.[4]

Medical education is no stranger to these alternative learning models, but it carries the added complexity of encompassing concepts that are both highly visual (e.g., anatomy) and rather abstract (e.g., immunologic processes). Therefore, medical school education routinely implements a variety of methods and modalities to best deliver a given topic.[5] Gross anatomy is traditionally taught with cadaveric dissection and two dimensional (2D) visual representations, while topics such as physiology and biochemistry rely more heavily on textbook readings and lectures. Technological advancement has led to the exploration of alternative modalities to augment, or even supplant, traditional methods such as slide-based lectures. Two of these modalities are 3D-printed models and augmented reality.

Slide-based lectures have been the standard for teaching modalities in higher education for many years. Its popularity is in part due to its ability to condense and organize large amounts of information as well as add visuals such as graphs, charts, and animations to supplement the lecture. Creating a slide-based presentation offers a relatively small learning curve, making it accessible to a wide majority of instructors. Further, the slides are easily stored and disseminated to students, allowing for review of the material at any time. There are a number of drawbacks to this method, however. This style of lecture often promotes passive learning and leads to less engaged learners.[6] Slide presentations are also limited to two-dimensional visuals and thus not ideal for topics that require understanding of complex three-dimensional structures.

Three-dimensional printed models are one of the potential solutions aimed at bridging this learning gap. With recent technological improvements, it is now possible to produce life sized, flexible, 3D replicas of real human organs. This provides learners with hands-on experience with complex structures and enables them to manipulate the models in a way that is not possible with modalities other than cadavers. Despite the technological advancements, the cost of producing 3D models is still high. It can cost as much as $65,000 for a printer, $15,000 for the software, and another $400 per hour to obtain the requisite computed tomography (CT) scans from which the models will be based[7]. Accurate utilization of the printers requires trained personnel, which further limits its use. Despite their portability, the excessive cost of the models limits student access outside the classroom, reducing opportunities for review.

Augmented reality (AR) is among the latest technologies being explored in medical education. This modality allows learners to visualize complex anatomy in three dimensions but does not offer the tangible element of 3D-printed models. AR offers an immersive and interactive experience allowing users to interact with the projected images without the physical constraints imposed by a 3D model. With the appropriate software, learners can “take apart,” zoom-in, and overlay models as they see fit. Being able to effectively use AR requires a comfortable level with its operation for all involved, which leads to a relatively steep learning curve when compared to other modalities. It requires personnel able to create the digital files of the teaching material and instructors who are familiar with the technology. Students unfamiliar with AR due to its novelty may experience a learning curve with the controls before utilizing it as a learning method. Lastly, AR can induce several side effects such as headaches and motion sickness which can adversely affect the learning experience.[8]

Each learning modality has clear benefits and limitations and with increasing availability has a growing potential to play a role in the future of medical education in some capacity.[9-16] This study aims to evaluate and compare the impact of traditional slide based lecture, 3D-printed models, and augmented reality on undergraduate medical students’ understanding of complex anatomical and physiologic concepts as well as their subjective experiences with the modalities.

Methods

A prospective randomized controlled study was conducted with first year medical students at Case

Western Reserve University in Cleveland, Ohio. Following IRB approval from Case Western Reserve University School of Medicine, students were recruited to participate in the study through emails and in-person announcements. Participation was voluntary and participants did not receive financial compensation. A standardized curriculum was developed to ensure equivalent subject matter was covered in each group. A slide-based lecture was created using PowerPoint and included text, static 2D figures, and basic 2D animations but did not include any videos or other media.

Using the Unity development platform, a new augmented reality application was developed to allow students an immersive experience using the HoloLens headset. Images were sourced from cardiac computed tomography angiography (CTA) images of de-identified patients with normal heart anatomy, tetralogy of Fallot (TOF) and hypoplastic left heart syndrome (HLHS). The CTA images were segmented using Realize Medical's Elucis VR software, to create high-fidelity 3D anatomic models. The models were printed in three colors to better represent and differentiate the cardiac anatomy: blue to represent right-sided heart structures, red for left-sided structures, and yellow for pathologic structures such as a patent ductus arteriosus. The virtual 3D anatomic models were then converted to compatible file formats and uploaded to the Unity app and subsequently downloaded on Microsoft HoloLens to deliver the augmented reality teaching. The same files were used to create a 3D printed model with the use of a Stratasys Medical 3D printer.

Participants were randomly assigned to one of three groups: 1) traditional slide-based teaching, 2) hands-on instruction with 3D-printed heart models, and 3) augmented reality (AR) instruction using HoloLens Headsets. Participants completed a 16-question pre-test consisting of four basic general cardiology questions and six questions each regarding the anatomy and physiology of TOF and HLHS. Participants then took part in a 30-minute teaching session using their assigned modality. Sessions were completed simultaneously, and each group utilized only the modality to which they were assigned (i.e., the 3D model and AR groups did not provide corresponding teaching slides). Upon completion of the teaching session, participants completed a post-test questionnaire consisting of the same 16 questions. A delayed post-test was conducted three weeks later with same questionnaire to evaluate the participants' knowledge retention. The delayed post-test also contained qualitative questions regarding their experience with the teaching session and use of the assigned modality. Confidentiality was ensured by not collecting any personally identifiable information from participants. Pre- and post-tests were linked using participant-created codes that did not contain personal identifiers.

The test was divided into three sections: general cardiology, TOF, and HLHS. For each participant, four scores (general score, TOF score, HLHS score, and total score) were recorded at the pre-test, post-test, and delayed post-test. Improvement scores were calculated by subtracting the pre-test score from the post-test and delayed post-test scores. A perfect score was defined as achieving the full total score (16 points) on the post-test and was recorded for each modality.

Descriptive statistics were used to summarize the distribution of participants' scores. Medians with interquartile ranges were reported for continuous variables, and frequencies with proportions for categorical variables. To compare scores across modalities, the Kruskal–Wallis rank-sum test and Fisher's exact test were applied to continuous and categorical variables, respectively.

To enhance the power to detect differences in score improvements from the pre-test to the post-test and delayed post-test across the three modalities, a difference-in-differences (DID) analysis was performed. This approach assessed the impact of each modality by comparing score changes over time. The DID model included an interaction term between modality and time point. To account for participant-level clustering, a random intercept was included using a mixed-effects model. All statistical analyses were conducted using R version 4.3.3.

Results

Twenty-six first-year medical students participated in the study. Eight were instructed by slide-based lecture, nine were taught using 3D models, and nine utilized the HoloLens augmented reality goggles. Seventeen of the twenty-six participants completed the delayed post-test. Table 1 shows the median total and individual category scores, as well as the interquartile ranges (IQR), for each modality. Figure 1 shows violin plots of these scores. Figure 2 shows the improvement in post-test and delayed post-test scores compared to pre-test scores for each modality.

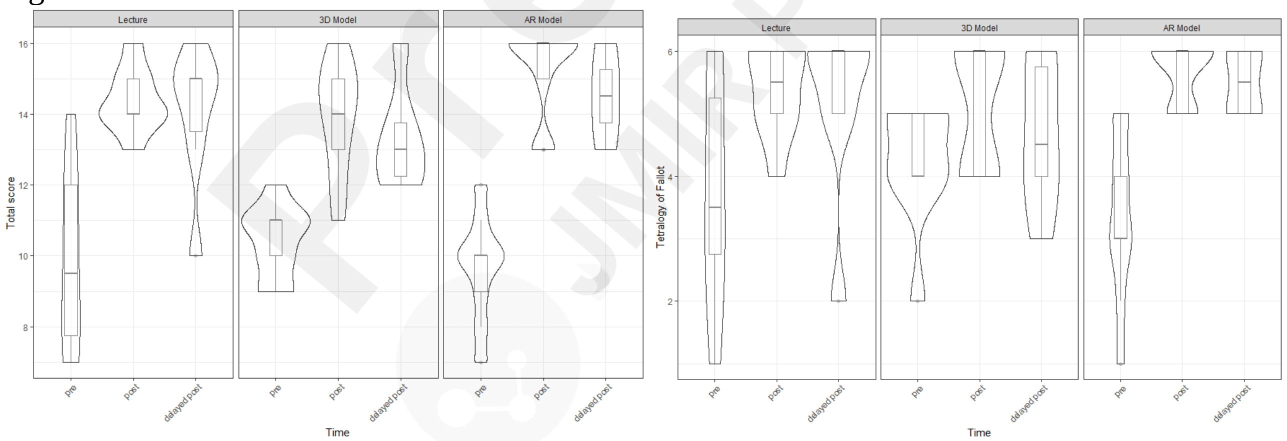
There was no statistically significant difference in total median scores of pre- and post-tests between the three modalities. There were also no statistically significant differences in subsection scores between modalities, though the immediate post-test scores for HLHS questions were very close (p=0.051) to showing superiority in the augmented reality group. Participants exposed to augmented reality teaching did obtain a perfect immediate post-test score at a significantly increased rate (p=0.024) compared to the lecture and 3D model groups, though this benefit was not seen in the delayed post-test (Figure 3).

Table 1: Median Scores (IQR) by Modality.

Questions	Lecture	3D Model	AR	p-value
	Pre-test Median (IQR)			
General	3 (2.75- 4)	4 (3-4)	3 (3-4)	0.2
TOF	3.5 (2.75-5.25)	4 (4-5)	3 (3-4)	0.4
HLHS	3 (3-3)	3 (2-3)	3 (2-4)	0.4
Total	9.5 (7.75-12)	11 (10-11)	10 (9-10)	0.6
	Post-test Median (IQR)			
General	4 (4-4)	4 (4-4)	4 (4-4)	0.8
TOF	5.5 (5-6)	6 (4-6)	6 (5-6)	0.5
HLHS	5 (5-5)	4 (4-6)	6 (6-6)	0.051
Total	14 (14-15)	14 (13-15)	16 (15-16)	0.1
	Improvement from Pre-test Median (IQR)			
General	1 (0-1)	0 (0-0)	1 (0-1)	0.13

TOF	2 (0-3)	1 (0-1)	2 (1-3)	0.12
HLHS	2 (2-2.25)	2 (0-3)	3 (3-4)	0.8
Total	5 (2.75-6.25)	3 (3-5)	5 (4-6)	0.2
	Delayed Post-test Median (IQR)			
General	4 (3.5-4)	3.5 (3-4)	4 (4-4)	0.3
TOF	6 (5-6)	4.5 (4-5.75)	5.5 (5-6)	0.5
HLHS	5 (5-5)	5.5 (4.25-6)	5 (4.75-5.25)	>0.9
Total	15 (13.5-15)	13 (12.25-13.75)	14.5 (13.75-15.25)	0.4
	Delayed Post-test Improvement Median (IQR)			
General	1 (0-1)	0 (-0.75-0.75)	0.5 (0-1.25)	0.3
TOF	1 (0.5-3)	0.5 (0-1)	1 (0.75-1.50)	0.3
HLHS	2 (1.5-3)	3 (2.25-3)	3 (2.5-3)	0.4
Total	5 (3-6)	3 (3-3.75)	4.5 (3.25-5.75)	0.5

Figure 1: Scores distribution at three test times for Each Modality



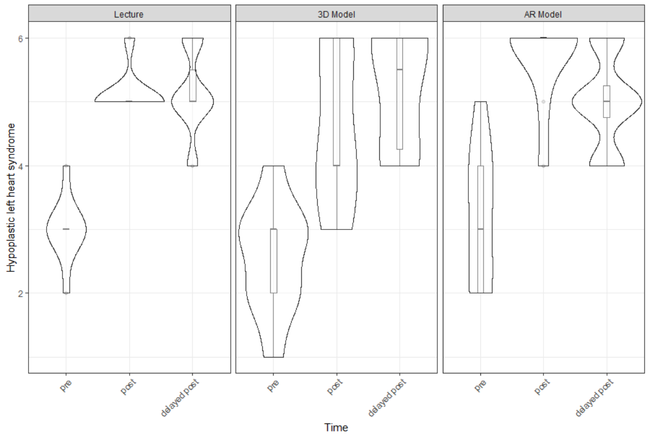


Figure 2.1: Difference in Post-Test Scores from Pre-Test for Each Modality

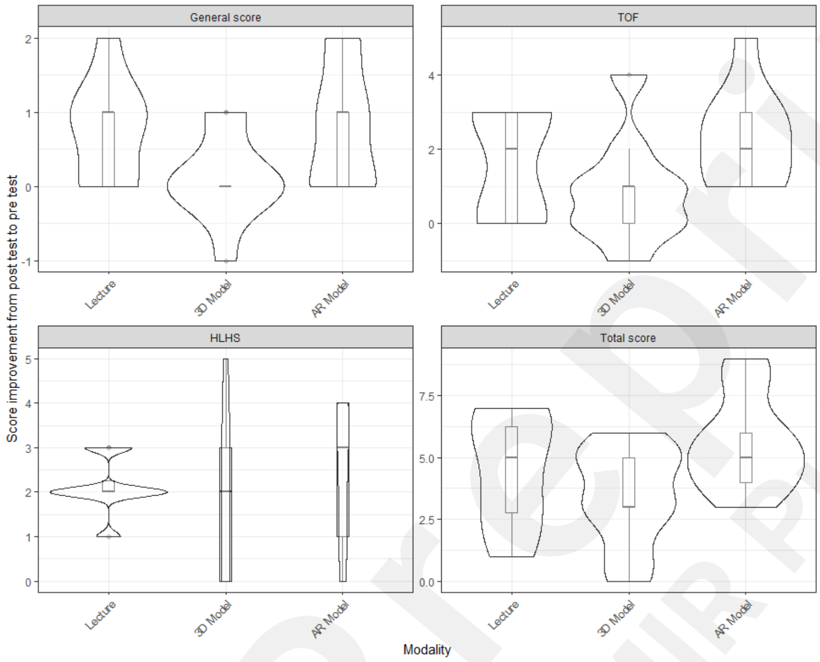


Figure 2.2: Difference in delayed Post-Test Scores from Pre-Test for Each Modality

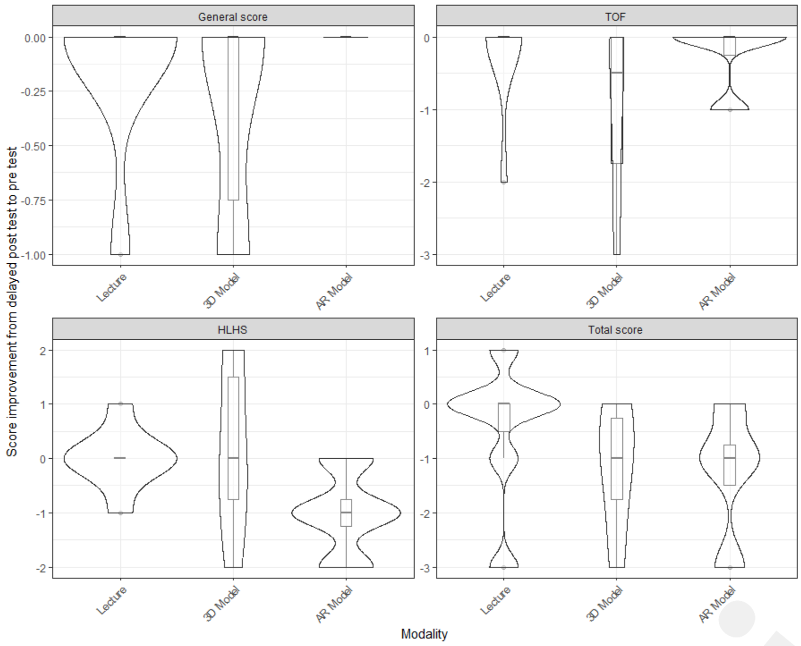


Figure 3: Perfect Scores Obtained on Post-Tests by Modality

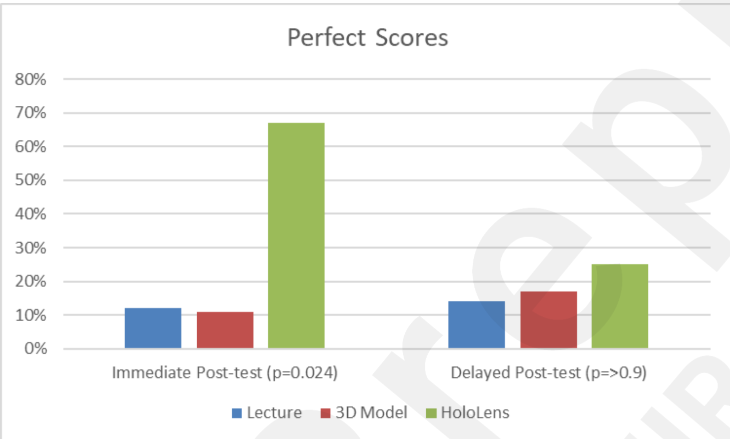


Table 2.1: Comparison of Score Improvements from Pre-Test to Post-Test and Delayed Post-Test Across Three Modalities, Using the 3D Model as the Reference.

	Lecture model	AR model
Difference of improvement score from post to pre		
General	0.64, 95% (-0.02, 1.3) p value= 0.06	0.67, 95% (0.03, 1.31) p value= 0.05
TOF	0.74, 95% (-0.45, 1.92) p value= 0.23	1.44, 95% (0.29, 2.60) p value= 0.02

HLHS	0.12, 95% (-1.04, 1.29) p value= 0.83	0.44, 95% (-0.68, 1.57) p value= 0.44
Total score	1.06, 95% (-0.77, 2.88) p value= 0.26	2.11, 95% (0.34, 3.88) p value= 0.02
Difference of improvement score from delayed post to pre		
General	0.76, 95% (0.05, 1.48) p value= 0.04	0.99, 95% (0.21, 1.78) p value= 0.02
TOF	1.13, 95% (-0.17, 2.43) p value= 0.1	1.58, 95% (0.13, 3.02) p value= 0.04
HLHS	-0.47, 95% (-1.72, 0.78) p value= 0.46	-0.83, 95% (-2.18, 0.52) p value= 0.23
Total score	1.33, 95% (-0.66, 3.32) p value= 0.2	1.79, 95% (-0.40, 3.99) p value= 0.12

Table 2.2: Comparison of Score Improvements from Pre-Test to Post-Test and Delayed Post-Test Across Three Modalities, Using the Lecture Model as the Reference.

	3D model	AR model
General	-0.64 95% (-1.3, 0.02) p value = 0.06	0.03 95% (-0.63, 0.69) p value = 0.93
TOF	-0.74 95% (-1.92, 0.45) p value = 0.23	0.71 95% (-0.48, 1.9) p value = 0.25
HLHS	-0.13 95% (-1.29, 1.04) p value = 0.83	0.32 95% (-0.84, 1.48) p value = 0.59
Total score	-1.06 95% (-2.88, 0.77) p value = 0.26	1.06 95% (-0.77, 2.88) p value = 0.26
delayed post to pre		
General	-0.76 95% (-1.48, -0.05) p value = 0.04	0.23 95% (-0.54, 1.01) p value = 0.56
TOF	-1.13 95% (-2.43, 0.17) p value = 0.1	0.44 95% (-0.98, 1.86) p value = 0.54
HLHS	0.47 95% (-0.78, 1.72) p value =	-0.37 95% (-1.7, 0.97) p value = 0.6

	0.46	
Total score	-1.33 95% (-3.32, 0.66) p value = 0.2	0.47 95% (-1.7, 2.63) p value = 0.68

The results of the DID analysis are shown in Table 2. A statistically significant difference in total score improvement from pre-test to post-test was observed between the AR and 3D models (mean difference = 2.11; 95% CI: [0.34, 3.88]; p = 0.02), indicating that the AR model led to a greater improvement in total scores compared to the 3D model. For the general category scores, participants in the lecture group showed a 0.64-point greater improvement than those in the 3D group (95% CI: [-0.02, 1.30]; p = 0.06). Additionally, participants in the AR group demonstrated a statistically significant 0.67-point greater improvement compared to the 3D group (95% CI: [0.03, 1.31]; p = 0.05).

Figure 4: Individual Trajectories of Test Scores Across Pre-Test, Post-Test, and Delayed Post-Test

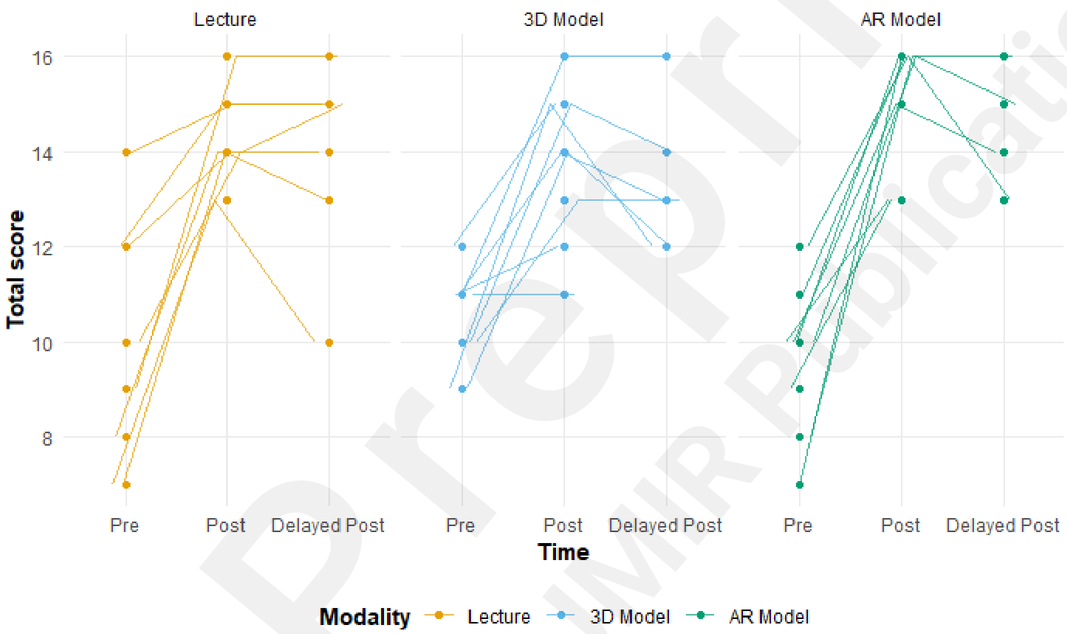
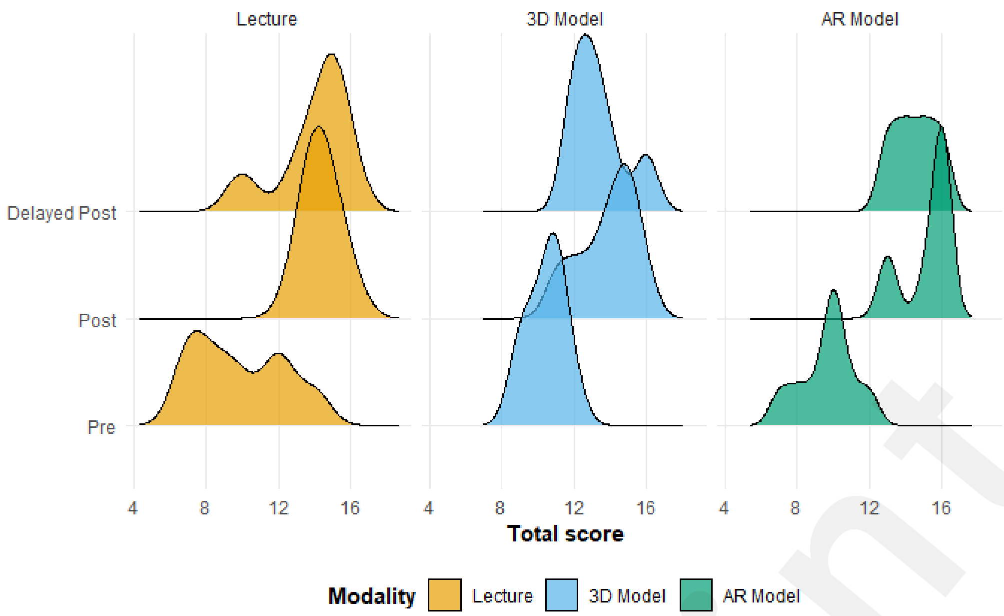


Figure 5: Temporal Changes in Score Distributions Across Educational Modalities



As shown in Figure 4 (individual) and Figure 5 (overall), the AR model demonstrated greater score improvement at the post-test compared to both the Lecture group (mean difference = 1.06, 95% CI: –0.77 to 2.88, p = 0.26) and the 3D model group (mean difference = 2.11, 95% CI: 0.34 to 3.88, p = 0.02).

However, both the AR model (mean change = –0.59, 95% CI: –2.75 to 1.57, p = 0.60) and the 3D-printed model (mean change = –0.27, 95% CI: –2.26 to 1.72, p = 0.79) showed a greater decline after the post-test when compared to the Lecture group.

Participants' subjective experiences were categorized by modality. Those who participated in the slide-based lecture reported the presence of diagrams and familiarity with the method as being most helpful in understanding the material. Participants who were part of the 3D-printed model and AR groups both reported the ability to visualize the cardiac defects as beneficial to their learning with the ability to physically feel the structures being an added benefit of 3D-printed models. A common drawback reported by lecture participants was a lack of three-dimensional or hands-on experience. Multiple participants expressed difficulty grasping the anatomy and physiology using only two-dimensional diagrams. Those in the 3D-printed model group noted difficulty manipulating the model to visualize internal structures. Some also reported a learning curve due to little or no prior experience with physical models. The primary downside noted by the AR group was intermittent glitches in the software.

Discussion

In this prospective randomized study of first-year medical students, we compared traditional slide-based lectures, 3D-printed models, and augmented reality for teaching congenital heart disease. While we found no statistically significant data to suggest superiority of any one modality over another in relation to overall test scores, several important trends emerged. Students in the AR group achieved perfect immediate post-test scores at a significantly higher rate than those in the lecture or 3D model groups and demonstrated greater score improvements from pre- to post-test, particularly in total scores and Tetralogy of Fallot questions. Difference-in-differences analysis confirmed a significant advantage of AR over 3D models in immediate knowledge gain, though this did not persist with the delayed post-test. Subjective feedback favored the 3D-printed model and AR groups, reporting that three-dimensional visualization improved understanding, while lecture participants had more difficulty conceptualizing structures with 2D diagrams.

Slide-based lectures remain a foundational component of medical education due to their efficiency and accessibility. However, their 2D format falls short when it comes to concepts that require a high degree of visuospatial understanding. This has led to the introduction of modalities such as 3D-printed models and AR into medical education curricula. In our study, students reported improved visualization, supporting the notion that 3D modalities may help address the gaps left by traditional teaching methods. Previous studies have compared 3D-printed models or AR to traditional methods.[9,11,12,16] Studies prospectively comparing all three modalities are, however, very limited.

Although the 3D-printed model and lecture groups showed no significant differences in total scores or score improvement, the students exposed to AR demonstrated statistically significant score improvement in multiple areas. The AR group also showed emerging trends suggesting superior total post-test scores. Participants who used the 3D-printed models and AR almost unanimously described the ability to better visualize the complex cardiac defects as a benefit of the modality while conversely those who were given a lecture felt the lack of a 3D component hindered their understanding. This suggests that students recognize the importance of 3D modalities in conceptualizing complex anatomy and physiology.

Participants in this study experienced teaching exclusively on their assigned modality, i.e., those who were taught using 3D-printed models or AR did not receive any supplementary slide-based presentation. White et al. performed a similar study comparing 3D-printed models to lecture in pediatric residents' understanding of ventricular septal defect (VSD) and TOF which showed improved understanding of TOF in the 3D-printed model group. However, in their study both groups were given the same lecture with the 3D-printed model incorporated into the intervention group's lecture.[9] Importantly, even without accompanying slide-based lectures, the 3D-printed model and AR groups in the present study performed comparably, or even superiorly, to the traditional teaching methods. These modalities are unlikely to fully replace traditional teaching methods, however these findings suggest they can serve as a powerful adjunct. Three-dimensional modalities can fill visuospatial gaps left by traditional teaching, leading to more complete learning of complex anatomical and physiologic concepts such as CHD. Further investigation is therefore needed to evaluate the efficacy of incorporation of these 3D modalities into traditional teaching methods.

Limitations:

The novelty of and comfortability with each modality potentially impacted the outcome. Students in this study were accustomed to AR technology as it is utilized routinely in their core curriculum. Therefore, they were not inhibited by the steep learning curve that can come with these devices. Conversely, they had little to no experience with 3D-printed models as a learning method. It is not surprising that students may gain relatively less understanding of a new and complex topic when also being given that information in a format that is unfamiliar to them. The students were undoubtedly intrigued by this modality as, following completion of the study, many students spent additional time interacting with the models. Therefore, the relatively smaller improvement following teaching with 3D models may be more a result of comfortability with the modality than the efficacy of the modality itself. Further studies involving participants who utilize 3D models as part of their standard curriculum and those unfamiliar with AR are warranted. Lastly, the small sample size limits the statistical power study of this study. A larger study across a more diverse student population is needed to build on these findings.

Conclusions

With advances in technology and the increased accessibility of these resources, we are seeing a paradigm shift towards the increasing use of 3D modalities in medical education and training. Owing to their visuospatial benefits, these modalities may serve as effective tools in medical education, contributing to improved student comprehension of complex anatomical and physiologic concepts. This study demonstrates an encouraging trend with augmented reality towards improving immediate understanding and short-term knowledge retention of complex congenital heart defects. This study provides insight into the benefits and limitations for the use of 3D modalities in medical education and emphasizes the importance of larger scale studies to guide their integration into medical education and maximize educational impact.

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Authors' Contributions:

Conceptualization – AA (lead), TL (equal), GB (equal), YLP (supporting), SWB (supporting)
Data curation – TL
Formal analysis – YZ
Funding acquisition – AA
Investigation – TL (lead), GB (equal), AA (equal), YLP (supporting)
Methodology – GB (lead), TL (equal), AA (equal), YZ (supporting)
Project administration – AA (Lead), SWB (equal), YLP (equal), GB (equal), TL (supporting)
Resources – GB (lead), AA (equal), SWB (equal)
Software – AA
Supervision – AA
Validation – AA (lead), GB (equal), TL (equal)
Visualization – TL (lead), GB (equal), YZ (equal), AA (supporting), SWB (supporting)
Writing – original draft – TL (lead), GB (equal), YZ (supporting)
Writing – review & editing – GB (lead), TL (equal), SWB (equal), AA (equal)

Conflicts of Interest: none declared

Ethical approval: IRB approval obtained through Case Western Reserve University

Abbreviations:

2D – Two dimensional
3D – Three dimensional
AR – Augmented reality
CHD – Congenital heart disease
CTA – Computed tomography angiography

HLHS – Hypoplastic left heart syndrome
TOF – Tetralogy of Fallot

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