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ORIGINAL ARTICLE

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Utility of three-dimensional models in resident education on simple and complex intracardiac congenital heart defects

Shelby C. White MD[1] | **Jennifer Sedler BS**[2] | **Trahern W. Jones MD**[3] | **Michael Seckeler MD**[1]

[1]Department of Pediatrics (Cardiology), University of Arizona, Tucson, Arizona

[2]University of Arizona College of Medicine, Tucson, Arizona

[3]Department of Pediatrics, University of Arizona, Tucson, Arizona

Correspondence
Shelby C. White, Department of Pediatrics (Cardiology), Banner University Medical Center – Tucson, University of Arizona, 1501 North Campbell Ave., Tucson, AZ 85724.
Email: shelbywhite@peds.arizona.edu

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Abstract

Objective: Applications of three-dimensional (3D) printed models in medicine include preprocedure planning, patient education, and clinical training. Reproducing complex anatomy as a 3D printed model can be useful for understanding congenital heart defects (CHD). We hypothesized that using 3D printed models during didactic sessions with resident physicians will improve trainees' understanding of CHD.

Design and intervention: We performed a prospective, randomized educational intervention for teaching pediatric and pediatric/emergency medicine residents about simple (ventricular septal defect [VSD]) and moderately complex (tetralogy of Fallot [ToF]) CHD. Residents were divided into two groups: intervention and control. Each group completed a subjective survey about their comfort with the anatomy, evaluation, and treatment of VSD and ToF and took an objective test on VSD and ToF. They separately received the same 20 min lecture, including projected two-dimensional digital images of VSD and ToF; the intervention group was given 3D printed models created using the same imaging data. After the lecture, the groups repeated the survey and test questions.

Results: Twenty-six residents participated in the VSD session, 34 in the ToF. There were no differences in demographics between control and intervention groups. All residents had higher subjective comfort with VSD and ToF after the lectures. There was no difference in baseline test scores for VSD or ToF groups. The control group scored higher on the VSD postlecture test. The intervention group scored higher on the ToF postlecture test.

Conclusion: Incorporation of 3D printed models into lectures about CHD imparts a greater acute level of understanding, both subjective and objective, for pediatric and combined pediatric/emergency medicine residents. There does not seem to be an added benefit for understanding ventricular septal defects, but there is for tetralogy of Fallot, likely due to increased complexity of the lesion and difficulty visualizing spatial relationships in CHD with multiple components.

KEYWORDS
medical education, pediatric cardiology, 3D printing, tetralogy of Fallot

1 | INTRODUCTION

Three-dimensional (3D) printing is a process in which layers of material are successively laid down to generate complex structures, which allows for the creation of relatively inexpensive prototypes.[1] Using imaging data from modalities such as computed tomography (CT) and magnetic resonance imaging (MRI), 3D printing has been used in the medical field to further advancements in prosthetics, undertake perioperative planning of complicated procedures, and facilitate clinical education.[2-6] Given the complex nature of congenital heart defects (CHD), 3D printing has been increasingly used in this field for anatomic modeling and procedural planning.[7] We have previously reported the utility of 3D printed models in modeling vascular rings and pulmonary slings for resident education.[8] The purpose of the present study was to explore the utility of 3D models of CHD in resident education for simple and complex intracardiac lesions, ventricular septal defects (VSD), and tetralogy of Fallot (ToF).

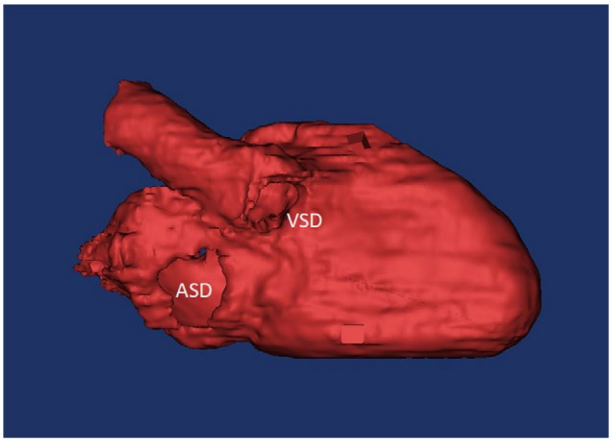

FIGURE 1 Computer generated 3D image of the left ventricular side of a heart with tetralogy of Fallot projected in 2D [Colour figure can be viewed at wileyonlinelibrary.com]

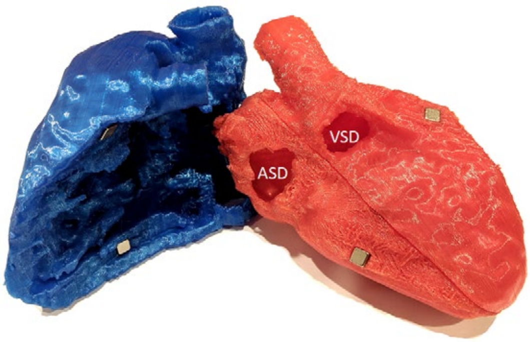

FIGURE 2 Printed 3D model of a right and left ventricle of a heart with tetralogy of Fallot [Colour figure can be viewed at wileyonlinelibrary.com]

2 | METHODS

After approval from the University of Arizona Institutional Review Board, CHD models were selected from our institution's previously generated 3D model library. In addition to using models of normal hearts, three types of VSDs were chosen—perimembranous, muscular, and outlet, as well as a model of ToF. Segmentation of the cardiac and vascular anatomy of interest was previously performed using Philips IntelliSpace Portal (Philips Healthcare, Best, The Netherlands), and stereolithography files were generated from these segments. Models were cleaned and prepared for printing using Autodesk MeshMixer (Autodesk, Inc, San Rafael, California) and printed with poly-lactic acid (PLA) on a Dremel 3D Idea Builder (Dremel, Mount Prospect, Illinois).[8]

Pediatric residents and combined pediatrics/emergency medicine residents at the University of Arizona were emailed for potential recruitment in the study. Subjects were recruited on a voluntary basis and randomly assigned to either the control or intervention group based on the order of their response (first responder—control group, second responder—intervention group, etc). Separate randomization was performed for the VSD and ToF lecture days. Participant demographics collected included age, gender, year in residency, and previous participation in a pediatric cardiology elective.

Two separate lecture days were established, the first for VSDs and the second for ToF. Control and intervention groups had separate lecture sessions on each day. Before the didactic lecture, subjective knowledge of VSDs or ToF was assessed by completing a 3-question survey graded on a 7-point Likert scale (1 indicating strongly disagree, 7 indicating strongly agree) regarding the participants' level of comfort with understanding, diagnosing and treating VSDs or ToF. This was followed by a 7-question, board-style test to assess their objective knowledge of VSDs or ToF. Each group then received the same 20-min lecture on VSDs or ToF, covering the anatomy, clinical significance, diagnosis, and treatment of such lesions. The lecture was the same for both groups, and included images from the virtual models used to generate the physical printed models (Figure 1). During the intervention group's lectures, four copies of 3D printed physical models of normal hearts and each CHD (Figure 2) were distributed for inspection. After the lectures, both groups repeated the survey and objective board-style test to assess their comfort with and postlecture knowledge of VSDs and ToF. The intervention group had a fourth survey question regarding the perceived benefit of the 3D printed model on their learning.

Demographics and pre- and postintervention subjective and objective scores were compared within the groups as well as differences between the groups. The increase in score from pre- to posttest was calculated as the difference in number of questions answered correctly. Normally distributed continuous variables were compared with *t* tests, nonnormally distributed variables were compared with Mann-Whitney U tests, and categorical variables were compared with chi-square test. Change in subjective survey scores were compared with the Wilcoxon signed rank test. Statistical analyses were performed with SPSS Statistics v23 (IBM Corp., Armonk, New York). Statistical significance was defined as $P < .05$.

3 | RESULTS

3.1 | Ventricular septal defect intervention

Fifty-six residents were approached for participation in the VSD study; 33 agreed to participate and 26 (46%) completed the study, with 12 in the control group and 14 in the intervention group. Baseline demographics were similar (Table 1).

For both the control and intervention groups, there was a statistically significant increase in subjective confidence in participants' knowledge of VSDs after the lecture (Table 2). There was no difference in the baseline objective test scores, and both groups improved after the lecture, with the control group scoring higher than the intervention group on the postlecture test (Table 3).

TABLE 1

	Control (n = 12)	Intervention (n = 14)	P
Female (n,%)	9 (75%)	12 (86%)	.635
Age (y)	29.3 ± 3.1	28.2 ± 1.9	.307
Year in training	2 (1, 2)	2 (1.8, 3)	.322
Prior cardiology elective? (n, %)	8 (67)	8 (57)	.701

Demographics of residents participating in Ventricular Septal Defect intervention. "Year in training" denotes the postgraduate year of education of the resident, ranging from categorical or combined residency intern (1) to fifth-year (5) Pediatric/Pediatric Emergency Medicine resident. Data are presented as n (%), mean ±standard deviation or median (interquartile range).

TABLE 2

	Prelecture	Postlecture	P
Control			
1. Anatomy of the defect	4 (3, 5)	6 (5, 6)	.005
2. Diagnosis of the defect	4 (3, 5)	6 (5, 6)	.003
3. Treatment of the defect	4 (3, 5)	6 (5.3, 6)	.003
Intervention			
1. Anatomy of the defect	4.5 (2, 5)	5.5 (5, 6)	.001
2. Diagnosis of the defect	5 (2.8, 5.3)	5.5 (5, 6)	.003
3. Treatment of the defect	4 (3, 5)	6 (5, 6)	.005
4. Utility of 3D models	-	6 (5, 7)	-

Pre- and postlecture survey results among the control and intervention groups for the Ventricular Septal Defect intervention, questions regarded comfort with anatomy, diagnosis, and treatment. Surveys were a 7-point Likert scale (1 = strongly disagree, 7 = strongly agree). Data are presented as median (interquartile range).

TABLE 3

	Control (n = 12)	Intervention (n = 14)	P
Pretest score (n)	2.84 ± 0.71	3.14 ± 0.86	.335
Posttest score (n)	6.0 ± 0.43	5.07 ± 1.14	.012
Score increase	3.16 ± 0.6	1.93 ± 1.3	.004

Pre- and postlecture objective test scores among the control and intervention groups for the ventricular septal defect intervention. Score increase is the increase in the number of questions answered correctly. Data are presented as mean ±standard deviation.

TABLE 4

	Control (n = 17)	Intervention (n = 17)	P
Female (n, %)	12 (71%)	10 (59%)	.721
Age (y)	30 ± 2.7	29.3 ± 2.8	.418
Year in training	3 (1, 3)	1 (1, 3)	.245
Prior cardiology elective? (n, %)	11 (65)	10 (59)	1.000

Demographics of residents participating in Tetralogy of Fallot intervention. "Year in training" denotes the postgraduate year of education of the resident, ranging from categorical or combined residency intern (1) to fifth-year (5) Pediatric/Pediatric emergency medicine resident. Data are presented as n (%), mean ±standard deviation or median (interquartile range).

3.2 | Tetralogy of Fallot intervention

Sixty-three residents were approached for participation in the ToF study; 34 (54%) agreed to participate and completed the study, with 17 in each group. Baseline demographics were similar (Table 4).

For both the control and intervention groups, there was a statistically significant increase in subjective confidence in participants' knowledge of ToF after the lecture (Table 5). There was no difference in the baseline objective test scores, and both groups improved after the lecture, with the intervention group scoring higher than the control group on the postlecture test (Table 6).

4 | DISCUSSION

This prospective educational intervention demonstrated that incorporation of 3D printed models of congenital heart defects improves resident understanding of tetralogy of Fallot but not simple ventricular septal defects. Our group previously reported the ability of 3D models to improve resident understanding of and comfort with extracardiac abnormalities (vascular rings and pulmonary artery slings), but this is the first study to show a measurable improvement in

TABLE 5

	Prelecture	Postlecture	P
Control			
1. Anatomy of the defect	5 (3.5, 5)	6 (5, 6)	.001
2. Diagnosis of the defect	4 (3, 5)	6 (4.5, 6.5)	.002
3. Treatment of the defect	3 (2, 5)	6 (5, 6)	.001
Intervention			
1. Anatomy of the defect	5 (2.5, 5)	6 (5, 6)	<.001
2. Diagnosis of the defect	4 (2.5, 5)	6 (5, 7)	<.001
3. Treatment of the defect	3 (1.5, 4.5)	6 (5, 6)	<.001
4. Utility of 3D model	-	5 (4, 6)	-

Pre- and postlecture survey results among the control and intervention groups for the Tetralogy of Fallot intervention, questions regarded comfort with anatomy, diagnosis, and treatment Surveys were a 7- point Likert scale, (1 = strongly disagree, 7 = strongly agree). Data are presented as median (interquartile range).

TABLE 6

	Control (n = 17)	Intervention (n = 17)	P
Pretest score (n)	3.06 ± 1.14	3.41 ± 1.06	.359
Posttest score (n)	5.29 ± 1.26	6.06 ± 0.66	.037
Score increase	2.23 ± 1.6	2.65 ± 1.3	.406

Pre- and postlecture objective test scores among the control and intervention groups for the Tetralogy of Fallot intervention. Score increase is the increase in the number of questions answered correctly. Data are presented as mean ±standard deviation.

understanding intracardiac CHD based on objective testing. Despite the numerous use of 3D printing in medical education, there is very little objective evidence in the literature of its efficacy. The present study demonstrates that 3D models are not only a tool for personalized medicine, but also a valuable educational tool in aiding comprehension of complex congenital cardiovascular abnormalities.

Both control and intervention groups for each form of CHD demonstrated an improvement in comfort level and objective knowledge following the didactic lectures. In the ToF educational session, the intervention group achieved a significantly higher average posttest score than the control group, suggesting that the 3D models are a useful adjunct to lectures for moderately complex intracardiac CHD. In the VSD educational session, the control group achieved a higher average score than the intervention group, suggesting that 3D models may not enhance resident understanding of less complex intracardiac defects. One explanation for these results is that ToF is a more complex form of CHD, with multiple anatomic abnormalities, whereas isolated VSDs are likely to be more easily visualized and understood without the aid of a physical model. 3D models of more complex congenital heart defects could have an impact on education while they may not be needed for understanding simpler lesions, like VSDs.

Prior studies report that 3D models enhance visuospatial learning, understanding, and recognition of anatomic structures in a manner superior to conventional methods of textbook and computer-based learning.[8-10] 3D models also hold the potential for increased quality assurance and individualized health care in cardiology through simulations and presurgical planning.[11-13] Physicians, residents, medical students, and other health professionals stand to benefit from this innovative technique in the anatomically complex field of pediatric cardiology.[14] Education for CHD differs from that of other anatomical education owing to the numerous structural defects as well as potential physiologic outcomes within defect types (ie, ToF vs transposition of the great arteries physiology for double outlet right ventricle). However, because of the infrequency with which CHD occurs in the general population, cadaveric donors of different defects are exceedingly rare. Because of this, CHD education would benefit from novel training methods that provide tangible structures not otherwise routinely seen.[15]

In addition to the uses already mentioned, there is potential for utilizing 3D models in medical education for various levels of education including medical school, residency, pediatric and adult cardiology fellowships, and nursing.[8,16,17] Many aspects of medical training could be improved by allowing trainees to obtain a physical representation of the involved structure before working with it in practice. This has already been shown to be useful in presurgical planning, and could be applied to multidisciplinary learning of specific lesions and defects in order to create more individualized care.[11,12] 3D models have also been used to enhance parent understanding of their child's specific anatomy.[18]

There are several limitations to this study. The first is that the group of participants was a cohort of pediatric and combined pediatrics/emergency medicine residents, and therefore, the findings may not be generalizable to other specialties or education levels. Second, the study was limited to two simple-to-moderately complex forms of CHD and may not be applicable to all forms of CHD. Additionally, our study only examined acute knowledge gain; further studies should be performed to assess long term retention of knowledge, and trainees' ability to apply such knowledge gain in clinical practice.

In conclusion, there may be a role for 3D models to improve education of more complex forms of congenital heart disease, like tetralogy of Fallot, when added to didactic sessions. Further studies are needed to determine efficacy for a variety of CHD and learner populations.

DISCLOSURE STATEMENT

The authors have no financial relationships relevant to this article to disclose.

CONFLICTS OF INTEREST

The authors have no conflicts of interest relevant to this article to disclose.

AUTHOR CONTRIBUTIONS

White helped conceptualize the project, performed resident lectures, reviewed, and edited the manuscript. Sedler helped draft the manuscript and assisted in collecting data. Jones helped conceptualize the project and reviewed the manuscript. Seckeler helped conceptualize the project, analyzed the data, reviewed and edited the manuscript.

ORCID

Shelby C. White http://orcid.org/0000-0001-6620-9956
Michael Seckeler http://orcid.org/0000-0001-9013-5723

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