ELECTRONIC JOURNAL OF MEDICAL AND EDUCATIONAL TECHNOLOGIES
https://www.ejmets.com
ISSN: 2754-544X (Online)

To cite this article: Bandaru V, Wagnon C, Meeks H, Pendse R, Bettarelli D, Cacao R, Piepkorn M, Kaur G. Efficacy of a congenital cardiac defect training model in embryological education for first-year medical students. ELECTR J MED ED TE. 2025;18(1):em2504. https://doi.org/10.29333/ejmets/17187

Original Article

Efficacy of a congenital cardiac defect training model in embryological education for first-year medical students

Vishal Bandaru [1*], Coltyn Wagnon [1], Hayden Meeks [1], Rohan Pendse [1], Douglas Bettarelli [1], Rafael Cacao [1,2], Melissa Piepkorn [1,3], Gurvinder Kaur [4]

[1] School of Medicine, Texas Tech University Health Sciences Center, Lubbock, TX, USA
[2] Department of Industrial, Manufacturing, & Systems Engineering, Texas Tech University, Lubbock, TX, USA
[3] Neonatal Intensive Care Unit, University Medical Center, Lubbock, TX, USA
[4] Department of Medical Education, Texas Tech University Health Sciences Center, Lubbock, TX, USA
* Corresponding author: Vishal Bandaru E-mail: vishal.bandaru@gmail.com ORCID: 0009-0004-9048-9416
Received: 27 May 2025 Accepted: 17 September 2025

ABSTRACT

Congenital heart defects (CHD) are a complex yet essential topic for medical students. This quality improvement project aimed to enhance CHD education through a lecture on anatomic defects supplemented with focused quizzes, and a training heart model featuring three embedded CHD. Initially, designed for 40 students, high demand led to the expansion of the lecture to 140 participants over two years (70 students in each year), with half attending sessions incorporating models and half attending without models. A significant increase in score from pre- to post-quiz ($p < 0.00$) was observed for both groups, though the difference between the model and non-model groups was not statistically significant ($p = 0.12$). Student feedback indicated that the lecture, quizzes, and models; 95.5% of students strongly agreed or agreed that the model was useful in conjunction with the lecture. These findings suggest that structured, interactive approaches can effectively reinforce CHD concepts in early medical education.

Keywords: education, medical, graduate, fetal heart, printing, three-dimensional

INTRODUCTION

Embryology has been gradually de-emphasized in medical school curricula due to time constraints, with recent national and international trends indicating a continued decrease in time dedicated to the subject [1]. A United States survey demonstrated a decrease in medical schools teaching embryology from 92% to 77% as of 2017 [2]. Additionally, they found that the average number of classroom hours spent on embryology excluding tests was 13 hours, with 11 hours being large group activities. Internationally, European studies have found both similar trends and a desire for increasing the amount of embryology and histology that is taught in their medical school coursework [3]. The trend of difficulty and low amounts of time spent was also mirrored in Asia, a study in Pakistan even found that 89% of medical students rated embryology as one of the most difficult subjects in anatomy [4]. The supplementation of embryological material may require adapting teaching mediums and extracurriculars interventions for medical students [5, 6].

Cardiology remains a challenging subject for medical students, largely due to the intricate interplay between anatomy, physiology, and pathology. At Texas Tech University Health Sciences Center-School of Medicine (TTUHSC-SOM), cardiac anatomy is introduced during the anatomy, histology and embryology (AHE) course. In AHE, the modality of teaching heart anatomy is compounded by embryological defects. In recent years, the emergence of three-dimensional (3D) printing as an adjunctive educational tool in cardiology has gained growing attention. Given the complexity of cardiac structures, especially in the context of congenital anomalies and valve pathology, cardiology greatly benefits from enhanced spatial visualization tools [7]. These tools help bridge the gap between basic anatomy education and clinical application, supporting students in interpreting imaging and understanding structural pathology.

Medical students are confronted with a large amount of information that must be understood and memorized in order to pass exams [8]. As such, the methodology in which students are given material changes the rate that knowledge can be acquired and applied. Cardiac anatomy and auscultation are instances where multisensory perception can have tangential benefits [9]. Due to the quick pace of medical school, TTUHSC-SOM, 10 weeks covers the entirety of the anatomy for a human body, cadaveric lab, models, and imaging. Medical students also need to understand the role and development of the current landscape of medicine as technological advances will be directly implemented in their future work environment.

Understanding congenital heart defects (CHD) is critical not only for passing exams but also for future practice in cardiology, pediatrics, neonatology, and surgery. Missing a CHD in neonates and pediatrics can result in serious cardiac complications, underscoring the importance of early, focused education on these conditions. This quality improvement project evaluates whether targeted CHD instruction enhances student comprehension of cardiac anatomy and embryology, aiming to better prepare students for both exams and clinical practice. With reduced lecture time dedicated to embryology, this project explores alternative approaches to integrate embryological content–using teaching assistants to curate a small-group extracurricular voluntary learning opportunity via lectures, quizzes, and models.

MATERIALS AND METHOD

Ethics

This study was approved by the Texas Tech University Health Sciences Center Quality Improvement Review Board.

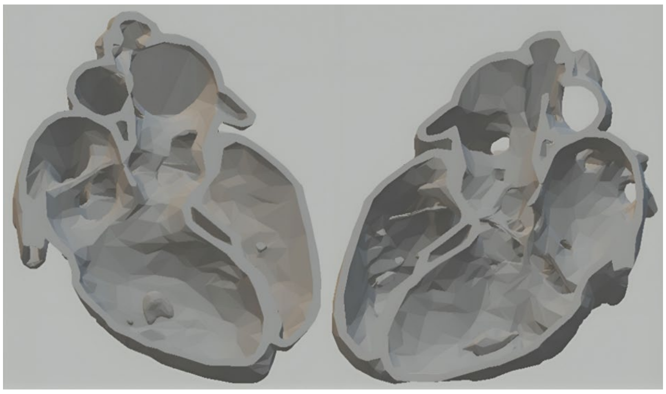

Figure 1. 3D heart model on 3D paint prior to printing and defect placements (Source: Authors' own elaboration)

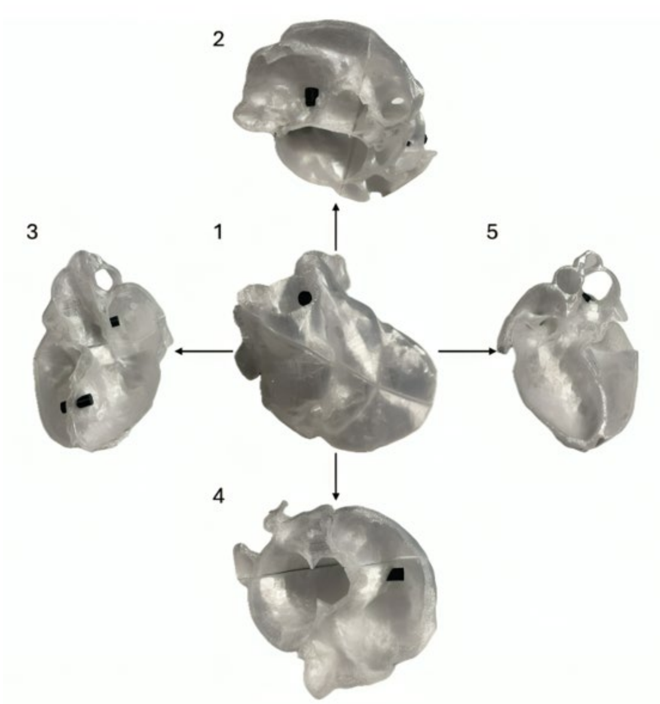

Figure 2. Printed model and cross sections with removable defects (Source: Authors' own elaboration)

Development of Neonatal 3D CHD Model

A team of medical students collaborated with [redacted for peer review] to develop the model, utilizing a de-identified adult chest computerized tomography scan to create a novel CHD model (**Figure 1**). The model incorporated key CHD features, including a patent ductus arteriosus (PDA), a ventricular septal defect (VSD), and an atrial septal defect (ASD), developed using a combination of the programs 3D Shapr, Microsoft Builder, and TinkerCAD. The final models were printed with Prusa3D printers using PLA filament, with variations in color (**Figure 2**).

Participants

An embryology lecture was given to medical students at TTUHSC-SOM following the completion of the CHD model. This session, led by [redacted for peer review], focused on

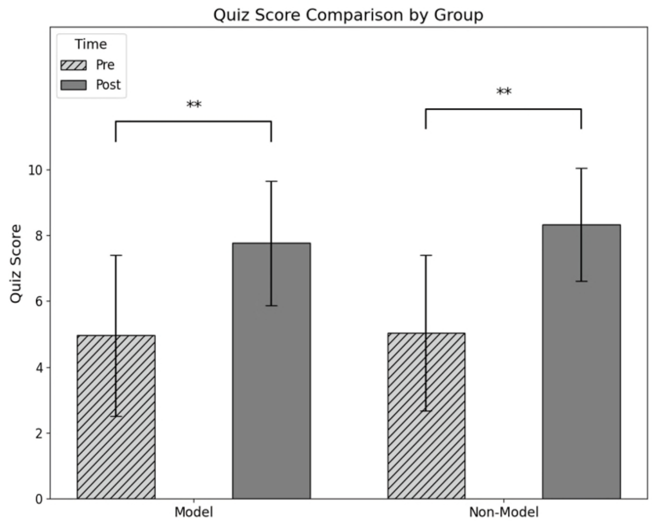

Figure 3. Quiz scores for model and non-model groups (Source: Authors' own elaboration)

CHD and was held on the weekend before the first AHE course exam where this material is being taught. During the review, students had the opportunity to study the 3D heart models. All first-year medical students enrolled at [redacted for peer review] (year 1 = 181 and year 2 = 182): were eligible for inclusion in this study. Only the participants who attended in-person sessions and quizzes were included in the study.

Knowledge Assessment and Student Feedback

To assess the effectiveness of the review session and the 3D heart models, a cardiac embryology lecture was supplemented with pre-, and post- quizzes. Due to limited availability of printed models and a high demand for the sessions, to accommodate all participants multiple (eight total) embryology lectures were given by two former teaching assistants. These included four model-based lectures (with ten students per session) and four non-model lectures (with ten students per session). Students in the model-based session had access to ten 3D CHD models along with the lecture and quizzes, while those in the non-model sessions received only the lectures and quizzes. Attendance was based on a first-come, first-served sign-up process and the availability of the models. Each session consisted of an optional 15-minute, 10 question pre-quiz (without correct answers or rationales), a 30-minute lecture, and a post-quiz identical to the pre-quiz, but with correct answers and rationales provided upon completion. At the end of the session, a QR code allowed students to evaluate the session, with additional questions for those who participated in the model session. This project was conducted over two consecutive years for medical students.

Statistical Analysis

The data analysis was conducted using Python with several key libraries. Pandas was used for data cleaning, transformation, and merging across different sheets and variables. NumPy and SciPy provided the core statistical functions, including t-tests, Mann-Whitney U tests, chi-square tests, and correlation analysis. Statsmodels was used for running logistic regression and generating detailed statistical summaries. For visualization, Matplotlib and Seaborn were used to produce plots such as boxplots, violin plots, scatter plots, and time-series line graphs with error bars and individual patient trends. An alpha of 0.05 was used to determine significance.

RESULTS

Student Performance on the Session Quizzes

Both the model and non-model groups completed pre- and post-quizzes (140 total students participated, 70 pre-quizzes and 70 post-quizzes from the model group and 70 pre-quizzes and 70 post-quizzes from the non-model group). A significant improvement in scores was observed from pre- to post-quiz in both groups ($p < 0.001$) (**Figure 3**). The model group has an average pre-quiz score of 49.5% compared to 50.2% in the non-model group. Post-quiz scores increased to 77.5% in the model group and 83.1% in the non-model group. However, no statistically significant difference in performance was found between the two groups ($p = 0.12$).

Student Perceptions of the Session and Quizzes

Following the interactive session, both the model and non-model groups completed a post- session survey (n = 45 for the model group and n = 43 for the non-model group over two years). Students rated their experience on a 5-point Likert scale, assessing the extent to which the lectures, pre- and post-quizzes contributed to stress reduction, enhanced their understanding of 3D anatomy, improved their comprehension of CHD, and increased their overall knowledge of the heart.

The lecture was reported to reduce stress, responses including both strongly agree and agree, by 93.7% of students in the model group and 94.1% in the non-model group students (**Figure 4**). In terms of increasing general cardiac knowledge and understating of CHD, 97.9% of the model group and 97.1% of the non-model agreed that the session was beneficial. A total of 79.1% of participants in the model group and 67.6% in the non-model group rated the lectures as effective for enhancing their understanding of 3D anatomy. A Mann-Whitney U test showed no statistically

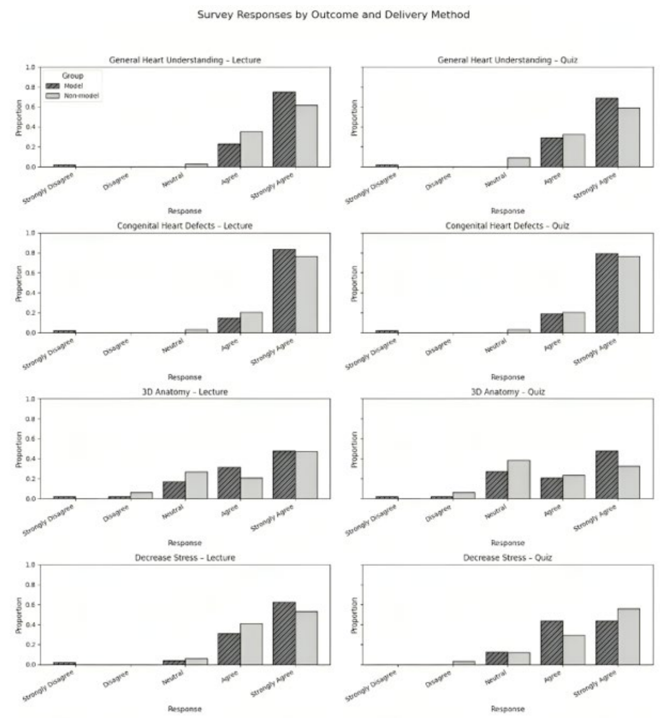

Figure 4. Lecture and quiz usefulness Likert scale ratings (Source: Authors' own elaboration)

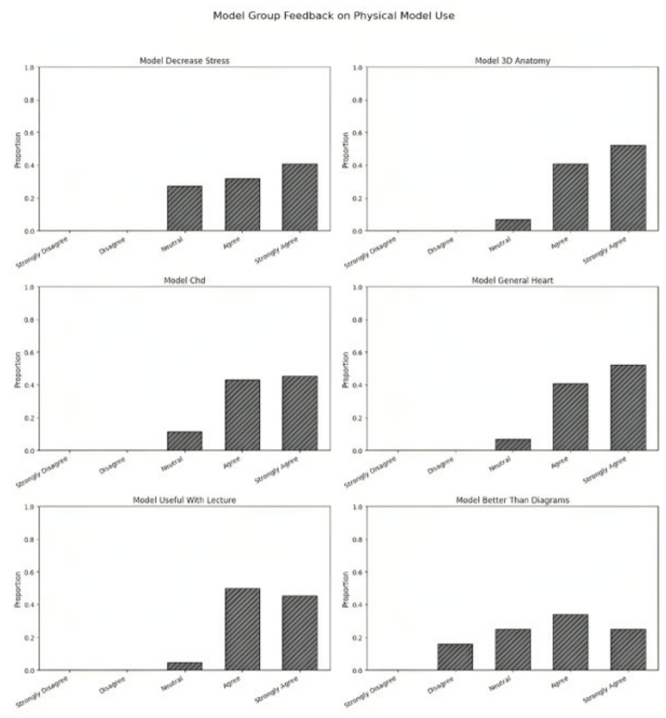

Figure 5. Model usefulness Likert scale responses (Source: Authors' own elaboration)

significant difference between groups in overall experience rating ($p > 0.05$ for all groups).

In the model group, 87.5% of students found the quizzes decreased stress while 85.3% of students in the non-model group found a decrease in stress (**Figure 4**). Both groups found a mixed result regarding the usefulness of the quizzes in teaching 3D anatomy, with 68.7% of the model group and 55.9% of the non-model group agreeing or strongly agreeing with the statement. In the model group, 97.9% of respondents agreed or strongly agreed that the quizzes enhanced both their CHD knowledge and general heart knowledge. In the non-model group, 97.1% reported improved increased CHD knowledge while 91.2% noted an increase in general heart knowledge. A Mann-Whitney U Test revealed no difference between the groups for overall rating of the experience ($p > 0.05$ for all groups).

Perceived Effectiveness of the 3D Heart Model

In the model group, 72.7% strongly agreed or agreed with the statement that the 3D heart model reduced stress and no students disagreed or strongly disagreed with that statement (**Figure 5**). The majority (88.6%) agreed that the model enhanced their understating of CHD. Additionally, 93.2% reported that the model improved both their general heart knowledge and comprehension of 3D anatomy. When asked about model's usefulness in conjunction with the lecture, 95.5% found it beneficial. However, only 59.1% agreed or strongly agreed that the model was superior to associated diagrams. Limited text feedback was positive with the only non-positive feedback being "more time with the models would help".

DISCUSSION

The frequency of CHD makes diagnosis and treatment important and medical students and practitioners are expected to be able to recognize these abnormalities and explain these defects to patients. Especially considering the demographic region of service, rural areas where access to obstetric and neonatal care is scarce, CHD may not be noticed until later in life [3-6, 10]. A retrospective study conducted in Atlanta reported that the prevalence of CHD is approximately 81.4/10,000 births [11, 12]. VSD, ASD, and PDA are the among the most common cardiac defects with VSD being the most prevalent [3-6]. The incorporation of cardiac embryology is of vital importance for both pediatric and neonatal patient populations. Medical students need to be able to recognize heart murmurs and pertinent patient history to suspect murmurs.

Medical education has found success with using 3D CHD printed models for teaching [13-18]. A 2019 meta-analysis of CHD 3D printing usage found 28 articles that had engaged in perioperative training, medical education, or patient education [7]. Of those 28 articles, twelve articles were related to medical education and seven utilized Likert scales to evaluate student preferences for models. When considering the four studies that were analyzed, medical education as a term grouped both residents and medical students in the meta-analysis. A study analyzing medical students found an improvement in test scores for both structural conceptualization and knowledge acquisition and found higher rates of satisfaction with CHD models [19]. A New York study found that their medical students found a positive linear correlation between the complexity of the CHD shown and the mean knowledge gained for the CHD relative to the model [17]. This trend was maintained in [15, 16], which found no difference between the groups.

When comparing the findings of our quality improvement project, we found that students had a high level of satisfaction with the model and that increase in 3D understanding is ranked the highest out of the teaching modalities used. The proportion of students that strongly agreed or agreed with the statement that the models increased 3D understanding in the model group was 93.2% whereas the lecture and quizzes were rated 79.1% and 68.7%, respectively. Interestingly, the models were rated at a lower rate than the traditional mediums, quizzes and lectures, for stress reduction statements. The models were rated similarly for general heart education and CHD education. Our quality improvement project indicates that medical students in both groups performed relatively well if the quality of the lecture material and quizzes are maintained. Medical students also commented in the feedback option that "more time with the models would help" and "I liked the small group setting for learning." The quizzes were designed to support exam preparation–not towards direct understanding of anatomical processes. Our study corroborates the literature findings of high levels of satisfaction and subjective engagement in the lecture with model usage [15-20]. However, our study does not find a difference between quiz performance for lectures that incorporated models and those that did not. Since the lectures were specialized for test content, the ability to explains the defects and confidence to explain the models were not evaluated, but the surveys indicate a greater understanding of 3D anatomy via the models. Verbal feedback from teaching assistants and the limited text feedback seems to indicate greater participation during the model sessions. As 3D printing continues to become more important in a growing number of medical specialties, both the process and usage of models will require more emphasis in both medical and residency training. We believe that student led medical innovations can create sustainable long-term solutions to problems with limited classroom time and small group settings.

A growing opportunity in medical innovation is one additional field that needs more exposure in medical school. Innovation in medical research and the need for early medical student involvement improves medical students career opportunities and necessary research skills [20, 21]. It was noted that medical education views leadership and entrepreneurship as co-curricular rather than as necessary for professional development and career enhancement [21]. The team of medical students followed similar principles to develop the model. The experience characterizes important skills such as applying for grants, solving technological problems, and bridging gaps in content knowledge between medicine and technology. To develop the heart models, the team of medical students participated in an 11-week plan to become comfortable with 3D printing. First, students learned how to work with 3D printing software such as Tinkercad and FreeCad. Segmentation for 3D printing was initially learned via 3D slicer. The medical student team worked to develop interlinking parts for the model and required multiple iterations to create a multi-piece heart with interlocking mechanisms. The process of developing the 3D heart models also left the medical students with transferable skills. Medical schools can seed opportunities with smaller grants in 3D printing and technological innovation to foster technological and entrepreneurial processes.

Researching optimal educational techniques in medicine has been fruitful in developing new methods to teach, including included flipped classroom sessions, team-based learning, and lottery-based token economy [22]. Additionally, educational research suggests that smaller group sizes are more conducive for education–a trend that has continually been of focus [23]. Implementing these techniques has been assisting medical school students with the quality of their education. Due to the focus on medical education and continually updating the most up to date guidelines, curating a personalized learning experience for students has become a forefront of self-led student education [24]. Students have great selection and have begun to use electronic resources at a higher frequency. Unfortunately, many of these modalities do not fully encompass tactile or positional relationships for anatomical structures. While medical students are improving their content and adapting to the large amount of growing medical literature, the ability to translate these skills into visual spatial ability is paramount in procedures [25]. The directionality and versatility of medical degrees makes expanding the content for medical schools difficult, especially with national trends of attempting to condense medical curricula. However, standardizing optional lectures as supplemental material for those that wish to enhance their knowledge on topics of interest or difficulty is a fair alternative to altering curricula. Small group setting sessions composed of teaching assistants or previous medical students may offer alternatives to formal class time considering the formal classroom time restrictions.

Limitations

Due to the high demand, the model group-limited to 40 students-filled within two hours of sign-up opening. To accommodate broader participation, a non-model group was added, as only 10 3D printed models were available. The decision to not include a larger class size was intentionally made to promote interactive learning. Additionally, this project was completely voluntary participation of medical students, and this was not a randomized control trial; therefore, results should not be generalized beyond the study context. Survey and quiz data was intended to assess the provision of equitable learning opportunity between groups, not as an indication of superiority of 3D models. Similarly, the quizzes were designed to support exam preparation rather than to evaluate understanding of 3D models. As a student led initiative, the models used may not match the quality of professionally manufactured anatomical models.

CONCLUSIONS

Medical education is difficult due to course rigor and many students find topics in embryology and anatomy particularly difficult. With a decreasing emphasis on embryology, alternative methods such as medical-student-led cardiac embryology lectures offer the ability to educate students on CHD. This quality improvement project found that the CHD lectures assisted in increasing medical student education and subjective Likert scale ratings indicate that CHD models can help with 3D anatomical understanding. Integrating custom 3D models into embryological lectures may offer students better understanding and positional orientation of

Author contributions: VB: conceptualization, data curation, funding acquisition, investigation, methodology, visualization, writing – original draft; **CW:** conceptualization, investigation, methodology, visualization writing – original draft, software; **HM:** conceptualization, investigation, methodology, validation, writing – original draft; **RP:** data curation, investigation, visualization, writing-– original draft, writing – review & editing; **DB:** data curation, investigation, visualization, writing – original draft, writing – review & editing; **RC:** formal analysis, data curation, writing – review & editing; **MP:** supervision, validation, visualization, project administration, funding acquisition, writing – review & editing; **GK:** supervision, project administration, writing – review & editing, validation, visualization, funding acquisition. All authors have approved the final version of the article.

Funding: This article was funded by the South Central Academic Medical Library Consortium in partnership by the methodology lab, TTUHSC libraries of the Health Sciences.

Acknowledgments: The authors would like to thank the Texas Tech University Health Sciences Center for the development of this study and the methodology lab for providing both the space and the trust necessary to develop CHD models for student education. The authors would also like to thank staff of the graduate school of biomedical sciences and the medical students whose participation was essential to the success of this study.

Ethical statement: This study was approved by the Texas Tech University Health Sciences Center Quality Improvement Review Board on 4 August 2023 with approval number QI-23059.

AI statement: The authors stated that no generative AI or AI-based tools were used.

Declaration of interest: Authors declare no competing interest.

Data sharing statement: Data supporting the findings and conclusions are available upon request from the corresponding author.

REFERENCES

1. Robertson AB, Oyedele O. The decline of embryology instruction within medical schools worldwide: Options for adapting. UBC Med J. 2019;10(2):39-40.

2. McBride JM, Drake RL. National survey on anatomical sciences in medical education. Anat Sci Educ. 2018;11(1):7-14. (doi:10.1002/ase.1760).

3. Carneiro BD, Pozza DH, Tavares I. Perceptions of medical students towards the role of histology and embryology during curricular review. BMC Med Educ. 2023;23(1):74. (doi:10.1186/s12909-023-04019-4).

4. Qamar K, Bashir S, Khalid R, Abaid M, Khadim R. Reasons for difficult topics in anatomy and their solutions as per undergraduate medical students. KHYBER Med Univ J. 2021;13(3):161-5. (doi:10.35845/kmuj.2021.21177).

5. Scott KM, Charles AR, Holland AJA. Clinical embryology teaching: Is it relevant anymore? ANZ J Surg. 2013;83(10):709-12. (doi:10.1111/ans.12213).

6. Meguid EMA, Holland JC, Keenan ID, Mishall P. Exploring visualisation for embryology education: A twenty-first-century perspective. Adv Exp Med Biol. 2022;1356:173-93. (doi:10.1007/978-3-030-87779-8_8).

7. Gharleghi R, Dessalles CA, Lal R, et al. 3D printing for cardiovascular applications: From end-to-end processes to emerging developments. Ann Biomed Eng. 2021;49(7):1598-618. (doi:10.1007/s10439-021-02784-1).

8. Blackman HJ. Anatomy and embryology in medical education at Cambridge University, 1866-1900. Med Educ. 2006;40(3):219-26. (doi:10.1111/j.1365-2929.2006.02395.x).

9. Patrizio HA, Phyu R, Kim B, Brolis NV. Improved cardiac auscultation competency interweaving visual, auditory, and tactile stimuli: A preliminary study. Int J Med Educ. 2024;15:37-43. (doi:10.5116/ijme.6607.27a6).

10. Marcus BS, Perez-Kersey P, Lee AB, et al. The performance of critical congenital heart disease screening in rural versus urban locations in the Northwest United States. J Pediatr Clin Pract. 2024;14:200120. (doi:10.1016/j.jpedcp.2024.200120).

11. CDC. Data and statistics. Congenital Heart Defects; 2024. Available at: https://www.cdc.gov/heart-defects/data/index.html (Accessed: 15 March 2025).

12. Bjornard K, Riehle-Colarusso T, Gilboa SM, Correa A. Patterns in the prevalence of congenital heart defects, metropolitan Atlanta, 1978 to 2005. Birt Defects Res A Clin Mol Teratol. 2013;97(2):87-94. (doi:10.1002/bdra.23111).

13. Botto LD, Correa A, Erickson JD. Racial and temporal variations in the prevalence of heart defects. Pediatrics. 2001;107(3):E32. (doi:10.1542/peds.107.3.e32).

14. Lau IWW, Sun Z. Dimensional accuracy and clinical value of 3D printed models in congenital heart disease: A systematic review and meta-analysis. J Clin Med. 2019;8(9):1483. (doi:10.3390/jcm8091483).

15. Karsenty C, Guitarte A, Dulac Y 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).

16. 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).

17. Smerling J, Marboe CC, Lefkowitch JH, 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).

18. Loke Y-H, Harahsheh AS, Krieger A, Olivieri LJ. Usage of 3D models of tetralogy of Fallot for medical education: impact on learning congenital heart disease. BMC Med Educ. 2017;17(1):54. (doi:10.1186/s12909-017-0889-0).

19. 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).

20. Chang Y, Ramnanan CJ. A review of literature on medical students and scholarly research: Experiences, attitudes, and outcomes. Acad Med. 2015;90(8):1162. (doi:10.1097/ACM.0000000000000702).

21. Suryavanshi T, Lambert S, Lal S, Chin A, Chan TM. Entrepreneurship and innovation in health sciences education: A scoping review. Med Sci Educ. 2020;30(4):1797-809. (doi:10.1007/s40670-020-01050-8).

22. Al-Hammouri MM, Rababah JA, Rowland ML, Tetreault AS, Aldalaykeh M. Does a novel teaching approach work? A students' perspective. Nurse Educ Today. 2020;85:104229. (doi:10.1016/j.nedt.2019.104229).

23. Ferreri SP, O'Connor SK. Redesign of a large lecture course into a small-group learning course. Am J Pharm Educ. 2013;77(1):13. (doi:10.5688/ajpe77113).

24. Wynter L, Burgess A, Kalman E, Heron JE, Bleasel J. Medical students: What educational resources are they using? BMC Med Educ. 2019;19:36. (doi:10.1186/s12909-019-1462-9).

25. Kalun P, Dunn K, Wagner N, Pulakunta T, Sonnadara R. Recent evidence on visual-spatial ability in surgical education: A scoping review. Can Med Educ J. 2020;11(6):e111-27. (doi:10.36834/cmej.69051).

◈◈◈