Virtual Reality in Medical Education: Innovative 3D application for teaching Congenital Heart Defects

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Abstract

Introduction
Medical education continues to face challenges relative to teaching complex human cardiac anatomy to a broad range of learners, especially in the subject of congenital heart defects. Traditional educational methods, such as cadaver dissection, textbooks and the study of human specimens, all face some limitations; e.g, such as specimen availability and student comfort. Employing newer technologies, like virtual reality (VR) offer a more profound learning experience for learners and mentors.

Methodology
Anonymized CT scans of patient heart images were used to create high-fidelity 3D cardiac models; employing Materialise Mimics Core and 3-matic Medical. These models were next integrated into an Unity powered VR application, designed for meta quest devices. Generated features, included: interactive 3D models, dynamic visualizations, and multiplayer functionalities for real time collaborative learning.

Results
Our VR application allowed users to interact with detailed 3D models of both cyanotic and acyanotic CHDs. Developed features include, allowing the user to generate multiplanar cuts and real time multiplayer visualization for collaborative teaching.
Conclusion
Our developed VR application offers innovative approaches for the teaching of complex cardiac anatomy including those of patients presenting with a CHD. Future work should focus on more readily available AI integrations for mobile devices and also adding more hearts and organs models, as well as performing long-term efficacy studies.

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Keywords: Medical education; Virtual reality; Congenital Heart Defects; Anatomy; Innovation.

Introduction

Background

Current curriculums in medical education often face the challenges of keeping pace with newly developed teaching methods: e.g., those introduced by technological advancements, such as the use of web applications, virtual reality (VR), and/or extended reality (XR) (1). The study of complexities and variations within human anatomy has historically been based on the uses of fresh cadavers, hearts preserved in formaldehyde, and/or the study of anatomy textbooks (2,3). Using new technologies for medical education, such as XR or VR, is of particular importance considering the complex spatial architectures with the human heart, this becomes even more complex when considering the cases of teaching congenital heart defects (CHD). These deviations from normal can be quite varies, hence presenting significant cognitive challenges for students; due to their intertwined vascular structures, dynamic relationships between structures, and/or the high degrees of variabilities of such defects that can occur within a given patient (4–6).

The uses of traditional dissection and the study of macroscopic anatomy as well as generated human models, while of particular importance in acquiring practical skills that are difficult to replace(7–9), are methods with numerous limitations. Today many medical school anatomy laboratories have difficulties maintaining adequate quantities of specimens in needed conditions for educational study. The practice of only studying surface anatomy falls short when one needs to understand complex anatomical details, such as: vasculature, complexities of nervous innervations, associated congenital heart defects, and other intricate aspects. It should also be noted that some students don't have access to a dissection opportunity and in others such environments can be a source of stress and anxiety (7,10–12). In this regard, the integration of Extended Reality (XR) technologies into medical education represents a significant advancement for many learners in the applications of better understandings of complex human anatomical and clinical knowledge required in healthcare or the medical device field.

XR technologies, is an umbrella term that encompasses Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR) educational tools (13,14). In general, VR is typically described as a computer-generated three-dimensional space that simulates the presence of physical objects through multisensory interactions, creating immersive experiences in which users perceive artificial worlds as if they were real. It can also be characterized by its capacity to be a computer-generated space where multiple users can have simultaneous access and thus participate in shared activities. (15–17). While different types of metaverse share common features such as Head-mounted displays (HMDs) for virtual immersions, motion tracking (6DoF) for real-time interactions, haptic feedbacks, and/or spatial audio to create a more immersive experience (15,18), VR differs from XR in that XR superimposes digital information on the users real surrounding physical environment. Again, VR completely isolates the user from the outside world, immersing the players in fully virtual simulated environments with which they can interact (15,19).

Prior work

According to recently reported studies on knowledge construction, perhaps a more effective way to better retain knowledge is through "active learning" or "learning by doing,". This implies that individuals better acquire critical knowledge through interactive and self-directed activities, such as those offered by virtual reality (VR) (20). The advantages of VR in education settings are that VR can be used in the absence of physical barriers. This also allows for collaboration among multiple users, which in turn generates a greater degree of freedom to create new applications or initiate new activities; i.e., through the virtualizations of knowledge in which students can engage in self-directed learning, allowing them to resolve their questions with a higher level of autonomy (6,21). Within the Visible Heart® Laboratory, virtual platforms with interactive 3D models have been successfully utilized by medical students and residents for training relative to both cardiac physiology and transesophageal echocardiography (22,23). By leveraging an extensive collection of over 650 perfusion-fixed human cardiac specimens, our laboratory continues to generate high resolution 3D computational models that in turn facilitate precise virtual placements of medical devices.

Additionally, multiple applications have been developed and utilized in the field of pre-surgical planning; using VR in our facilities, and the unique availability of an extensive range of fixed human hearts. This approach has been the cornerstone for generating multiple educational and collaborative tools such as our Stenting simulator, Seldinger technique guidewire simulator, and augmented reality applications like the “Heart to Learn App” (6,24,25).

To evaluate the relative efficacy of utilizing VR for human anatomic education, multiple research groups have consistently described the associated improvements this approach offers. For instance, Minouei and Liu *et al.*, in a systematic review, found that VR commonly enhanced the students’ academic progresses in terms of theoretical knowledge, practical proficiency, as well as overall satisfaction when used as supplementary methods to other teaching approaches (26,27). Similarly Baek *et al*. described 6 VR applications for the visualizations and study of anatomical structures. They recommend that the use of these applications should be tailored to the student's needs and suggested several ideal conditions for the uses of VR applications (28). Other educators have conducted a controlled clinical study, examining the roles of interactive 3D models in medical anatomy education; in such, 200 medical students were surveyed, and the results showed a statistically significant improvement in post-test knowledge when compared to the control group (29). Further, Garcia-Robles and Salimi *et al*., in their meta-analyses, demonstrated that XR generated increases in knowledge compared to traditional learning methods; especially when used with complementary resources. They noted that these learning approaches were most beneficial for undergraduate students, of whom 80% reported that when they used such VR tools that were useful for learning complex anatomies (30,31). Similarly, Liu and Wang *et al.* reported a higher satisfaction rating in groups of healthcare workers and students who used VR compared to other learning methods (27).

Noteworthy, it is also important to consider the limitations of VR use in some individuals; which can generate adverse effects such as visually induced motion sickness (VIMS). In a pilot study, VIMS was reported in 32% of participants, of which 40% stated that experiencing VIMS could negatively impact their learning process when using VR educational tools (32).

One should also consider that gaps currently persist in the specific implementation of video game engines for applications in educational cardiac modeling; this is particularly true in the field of congenital heart defects (CHD) (33,34). Our present study proposes an innovative pipeline that combines high-fidelity 3D modeling based on real tomographic data with dynamic visualization of myocardial layers and blood volume, and the implementations of such in Unity 3D with customized haptic interactions (35). Thus, our work should contribute to the field of digital medical education by providing a reproducible framework for developing immersive cardiac simulators, while simultaneously addressing technical and pedagogical aspects. Note, that unlike commercial VR solutions, our approaches prioritize didactic customizations, facilitating curricular adaptations.

Materials and methods

The employed methodologies of our work were developed in several sequential stages, beginning with the acquisitions and processing of medical images. First, anonymous DICOM images from patients were obtained through computed tomography (CT) from cases shared by Hospital La Cardio (Bogotá, Colombia) and from the anonymous database within the Visible Heart® Laboratories, (University of Minnesota, Minneapolis, USA). These image datasets were processed using Materialise Mimics Core 27.0 software, to perform semi-automatic segmentation of cardiac structures. As these investigations and development of de-identified 3D computation models did not directly involve human participants or use identifiable personal data: i.e., it did not require approval from an ethics committee.

In general, the segmentation process included automatic image alignments to ensure anatomical symmetry, followed by blood volume segmentations of ventricles, atria, and great vessels using adaptive thresholding (HU: approximately 200 to 1500) via the software's CT Heart tools. For a given heart, specific cardiac defects were identified, such as: interventricular communications, interatrial communications, patent ductus arteriosus, and/or others. Anatomical borders were manually refined using the Edit Masks function, achieving precision up to 1 mm, and internal hollowing was applied to simulate cardiac cavities.

Subsequently, these segmented congenital heart models were exported to Materialise 3-matic Medical 19.0 for optimization and final 3D modeling. At this stage, topological mesh repair was performed, eliminating non-manifold triangles, and cardiac valves were added using a parametric model library, adjusting their scale to the specific dimensions of each patient's heart. Anatomical textures were applied, and surfaces were smoothed using the Smooth Surface software module. The final models were exported in OBJ format, with mesh parameters optimized for VR performances.

During the development of the VR based educational application, Unity software 2021.3 LTS with XR Interaction Toolkit 2.3 was used. The generated 3D heart models were then obtained from 3-matic and were imported to Unity as optimized mesh assets. To ensure complete visualizations of the cardiac structures, backface culling was disabled, letting the users to actively "cut" into the heart and analyze the internal structures of the given 3D heart model.

To optimize anatomical accuracies, custom shader based materials were added with deoxygenated and oxygenated blood volumes color-coded with blue and red, respectively, as well as myocardium rendered in flesh tones, and the various pathological defects were highlighted: remaining visually coherent under dynamic real-time clipping system, developed using shader programming.

A floating in-world Canvas menu, was designed using Unity's XR Ray Interactor system, allowing for the users to have seamless navigations between heart models, toggling different cardiopathies and scrolling texts. Beyond single-user exploration, this unique educational application was designed to support real-time multiplayer interactions, using Unity's Netcode for GameObjects (NGO): users can communicate in real time using integrated Vivox Voice Chat and Photon PUN networking.

While the initial release targets PC-based VR setups, a standalone version was optimized for lower-performance hardware using texture compressions, and GPU instancing to maintain rendering efficiency. Compatibility with OpenXR ensures broader accessibilities across multiple headsets, including the Valve Index, HTC Vive, and Oculus Rift.

Results

Our developed educational application includes a floating menu that categorizes heart defects into cyanotic and non-cyanotic **(Fig. 1)**; with dynamic descriptive text incorporated within relative to each heart condition to be studied and explanatory images of predictive blood flows. Users have the ability to move the menu in the VR space as needed. The main functionalities allow users to manipulate cardiac models, including scaling, free rotations, and the abilities to perform multiplanar cuts using Shader Graph. Additionally, there is an incorporated pointer feature which any of the users can use to mark the given defect to be mentioned or mark a specific location on the heart **(Fig. 2)**.

Multiple users can also freely interact with a heart with normal anatomy, which is animated to visualize how different structures of a normal heart, such as valves and myocardial walls, interact during the cardiac cycle of systole and diastole. Additionally, users can interact with various pathological models adapted from real tomographies, such as: for non-cyanotic heart defects, a ventricular septal defect (VSD), a sinus venosus type atrial septal defect (ASD) **(Fig. 3)**, a patent ductus arteriosus (PDA), an atrioventricular septal defect (AVSD), a coarctation of the aorta (CoA); and for cyanotic heart defects, with truncus arteriosus, transposition of the great arteries, and tetralogy of Fallot (ToF) **(Fig. 4)**.

To facilitate collaborative teaching, a multiplayer architecture was implemented using Netcode for GameObjects, allowing synchronization of 3D models and actions across multiple devices in different global locations **(Fig. 5)**. This enables the use of a virtual classroom where the teacher has the abilities to instruct anatomy classes in real-time, point out defects with simultaneous visualizations by students, and guide anatomical tours, while students can access interactive menus and communicate with each other as well as the teacher for more immersive experiences.

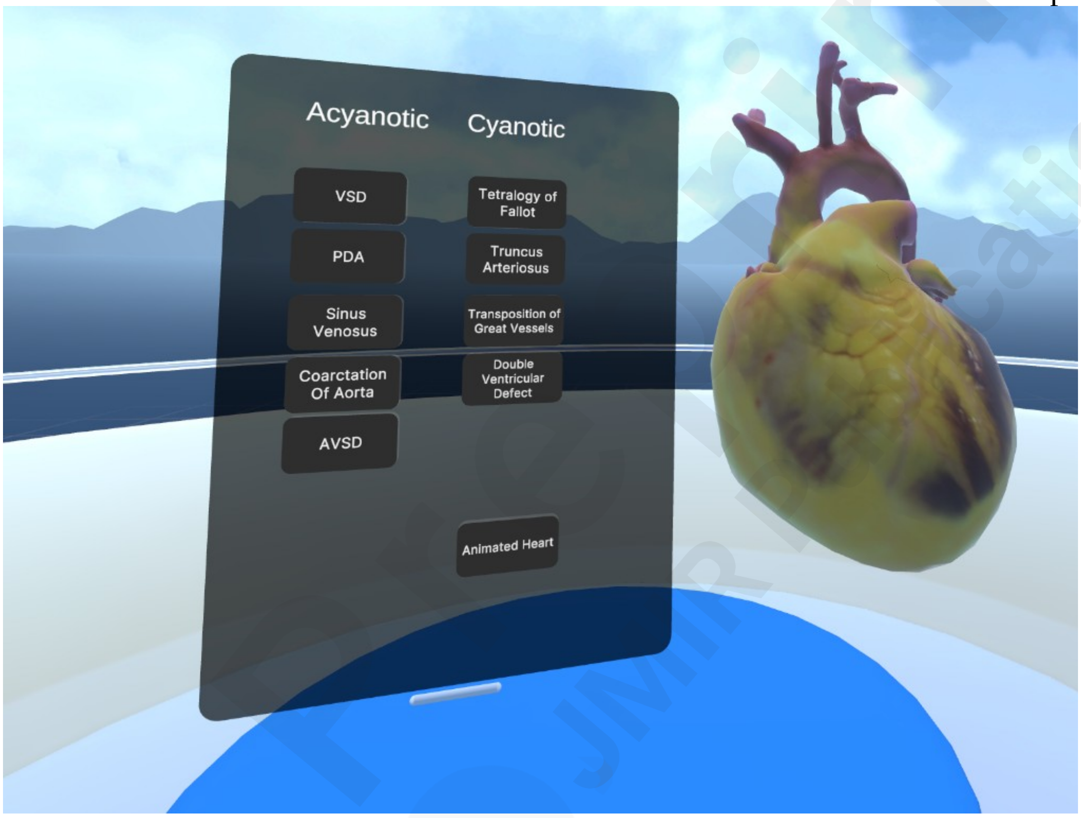

Fig. 1 Congenital Heart Defects floating menu with animated normal heart.

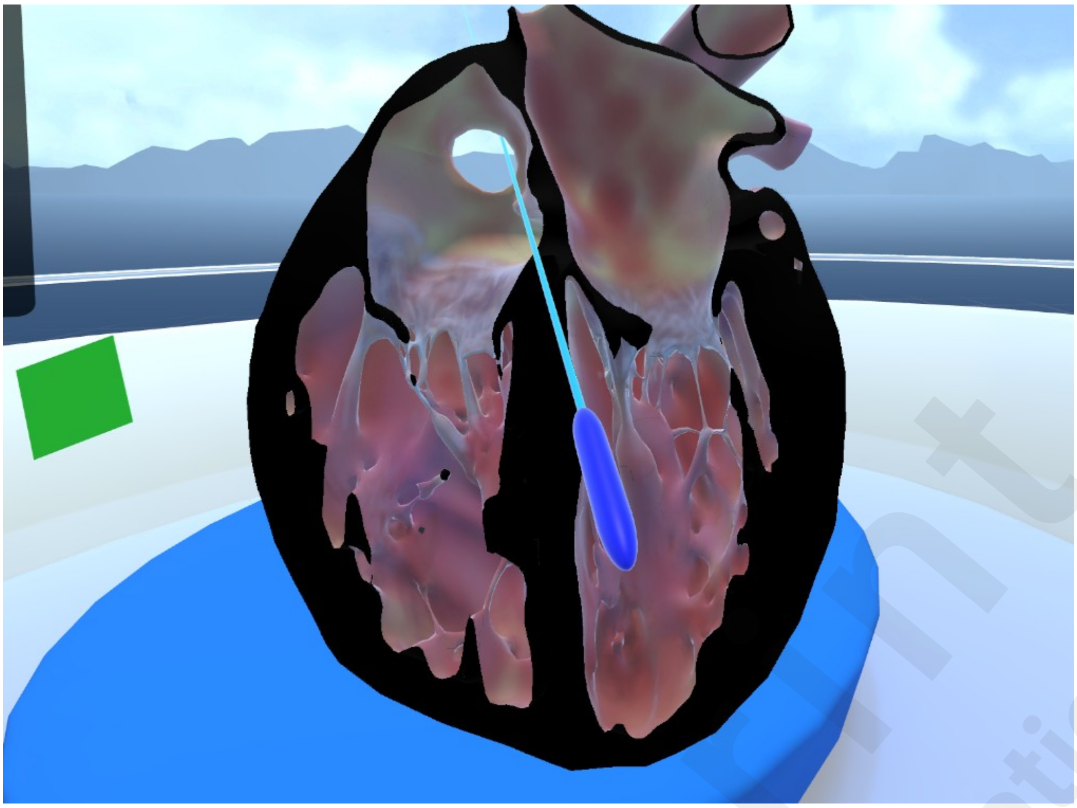

Fig. 2 Pointer and plane cutting VR tools.

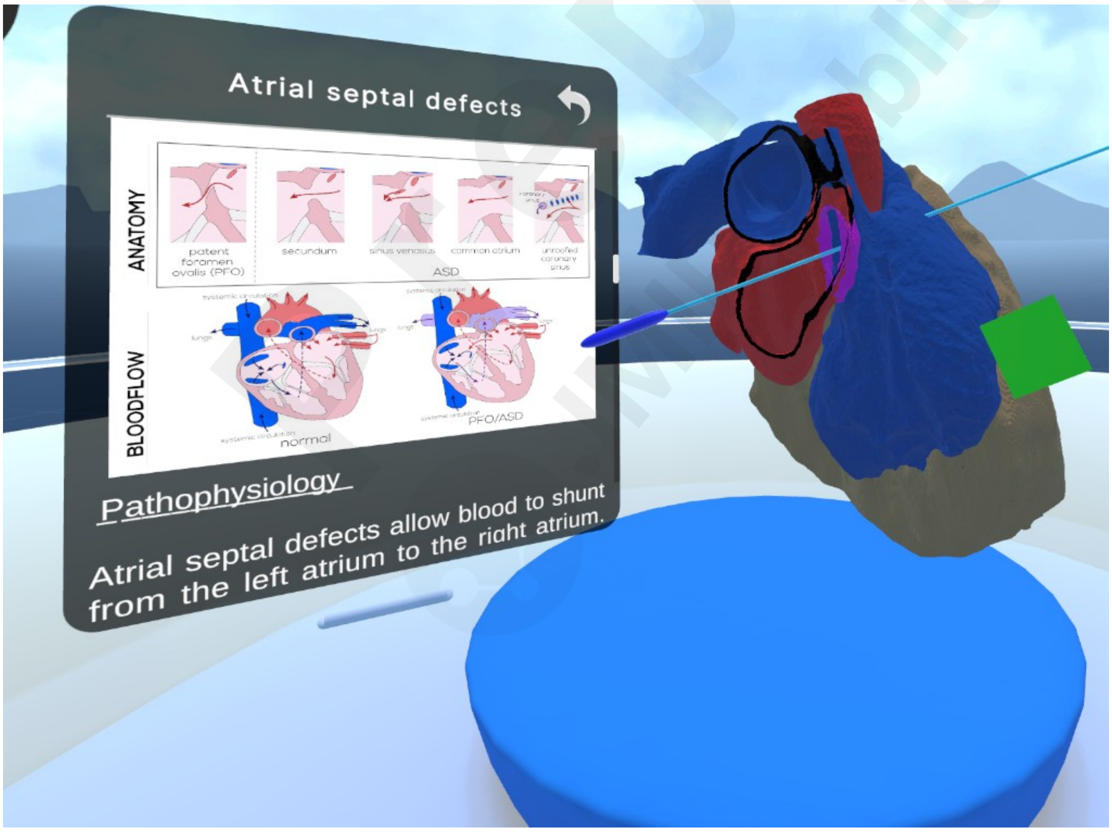

Fig. 3 Atrial Septal Defect (Type Sinus venosus) heart model.

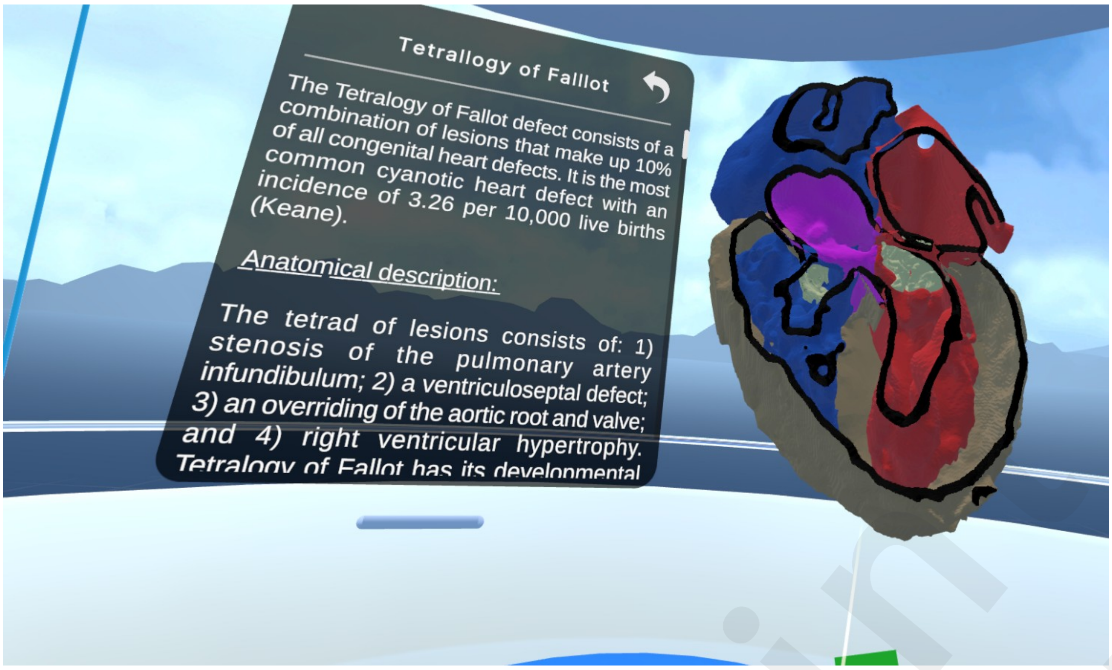

Fig. 4 Tetralogy of Fallot heart model.

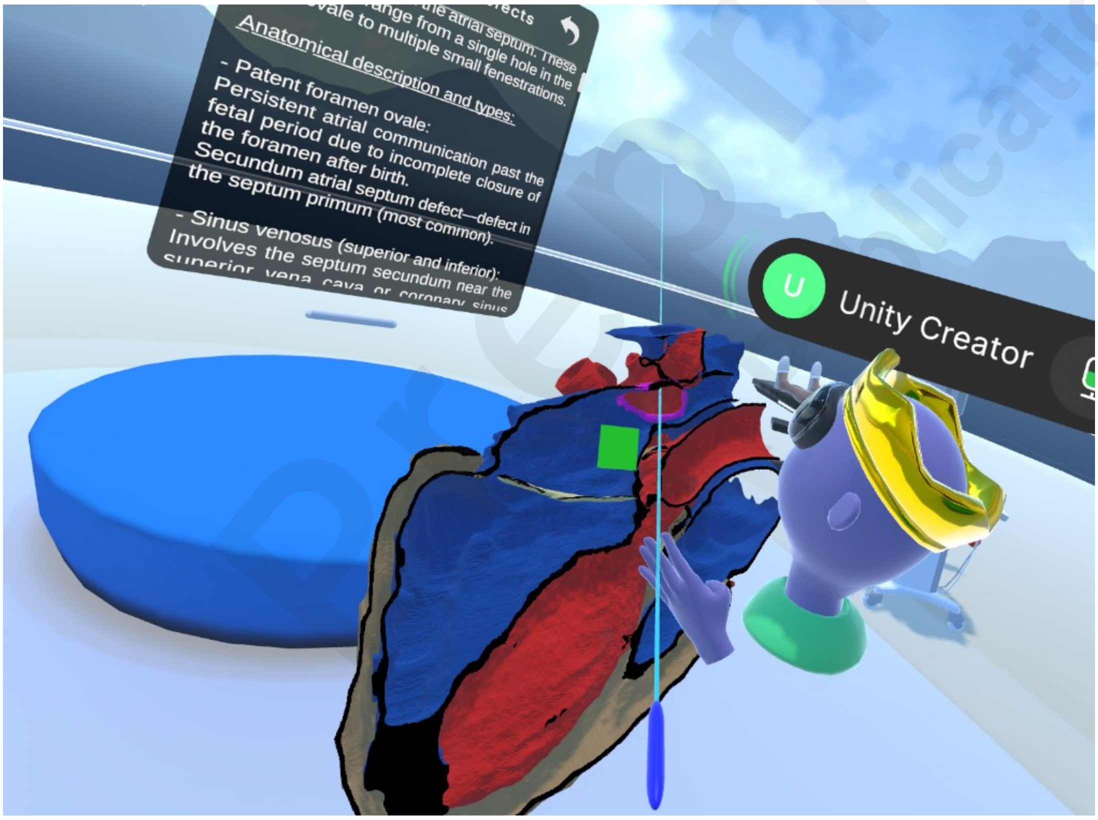

Fig. 4 Collaborative multiplayer environment.

Discussion

Our present educational tool is an innovative virtual reality (VR) application for teaching complex human cardiac anatomy, there exist other similar applications (33,34), but we have uniquely integrated high-fidelity 3D models based on real medical images. Additionally, this application can be utilized simultaneously by multiple international users which represents a significant advancement in digital medical education.

Developed educational VR applications in general offer multiple advantages over traditional learning methods. Here we discuss the abilities to allow for multiplayer visualization, real-time interactivity with complex cardiac structures, active and collective learning in a virtual classroom, and increased accessibility. These features require the use of VR, a valuable supplement to traditional education methods, potentially helping to reduce stress and anxiety for some students (10,30,31); but some may induce undesired side effects.

To date, feedback on our application from users, align with other authors who have developed anatomical learning apps such as Sharecare YOU Anatomy, 3D Organon VR Anatomy, Human Anatomy VR, Everyday Anatomy VR, and VR4Health. (28,34): in which VR educational tools have been shown to improve students' practical skills and overall satisfaction.

Despite its potential learning advantages, it is important to consider some limitations of VR use, which can cause adverse effects such as visually induced motion sickness or "cybersickness" that may negatively impact or even limit the uses of these learning experiences for some users. (32,36), Additionally, the technological learning curves can vary from user to user, depending on their initial familiarities with controls and video game usages. Further for some, implementation costs can also be a factor, including: expenses associated with hardware, software, and human resources such as systems engineers, computer scientists, graphic designers, healthcare personnel, and researchers, among others (6). Additionally, a potential novelty bias associated with VR educational technologies by some instructors should be acknowledged.

For future research relative to the utilization of these educational tools, it would be valuable to incorporate the uses of artificial intelligence (AI) with a knowledge database on congenital heart diseases. This could be used to provide real-time feedback with greater student autonomy, allowing for increased numbers of anatomical models, and improve their quality through multidisciplinary collaborations with other professionals. Furthermore, long-term comparative controlled clinical studies should be designed and performed associated with our developed VR platform, to assess knowledge retention in students and/or patients with congenital heart diseases.

It is important to also consider other ethical implications of using VR of real patient anatomies in medical education. Additionally, the costs of such technologies could in part create educational inequalities in regions with fewer economic resources. Finally, it is essential to ensure that students do not develop an excessive dependence on VR, neglecting other essential practical skills such as direct tissue manipulations and/or dissections.

Conclusions

The VR educational application we present is an example of the important modernization within medical education: our supplementary resources could potentially be effective tools for teaching congenital heart defects (CHD). Furthermore, its ongoing development and continuous collaboration between multiple research centers and academic institutions could have a substantial impact on the training of future healthcare professionals and in patient education. The VR platform we described here could help all types of learners better understand CHDs, provide a means for clinicians around the world to discuss complex CHD and treatment approaches, as well aid medical device designers relative to future innovations.

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Conflict of interests disclosure statement
There are no conflict of interests between the authors of this study.

Abbreviations
VR: Virtual reality
XR: Extended reality
AR: Augmented reality
MR: Mixed reality
HMDs: Head-mounted displays
6DoF: 6-Degree of freedom
CT: Computerized tomography
3D: 3-Dimensional
CHD: Congenital heart defects
VIMS: Visually induced motion sickness
DICOM: Digital Imaging and Communications in Medicine
HU: Hounsfield Units
NGO: Netcode Game Objects
GPU: Graphics processing unit
PUN: Photon unity network
HTC: High Tech Computer
VSD: Ventricular septal defect
ASD: Sinus venosus type atrial septal defect
PDA: Patent ductus arteriosus
AVSD: Atrioventricular septal defect
CoA: Coarctation of the aorta
ToF: Tetralogy of Fallot

Data availability statement
The data that support the findings of this study are available on request from the corresponding author. The data are not publicly available due to privacy or ethical restrictions.

Ethics statement
The medical images used in this study were originally obtained for clinical and educational purposes, with informed consent secured from patients at the time of imaging for educational and research

uses. Following their initial clinical use, associated images were anonymized to ensure patient confidentiality. No additional consent was required during the development of this study, as the anonymized data posed no risks to patient privacy. This study adheres to the ethical principles outlined in the Declaration of Helsinki, ensuring compliance with international standards for the ethical use of human data in research.

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All materials used were produced by use, thus we did not use copyrighted material.

References

1. Li Z, Li Z, Peng C, Zhao M, He Q. A Bibliometric Analysis of Virtual Reality in Anatomy Teaching Between 1999 and 2022. Front Educ [Internet]. 2022 Jul 19 [cited 2025 Feb 3];7. Available from: https://www.frontiersin.org/journals/education/articles/10.3389/feduc.2022.874406/full
2. Baek SW, Yeo T, Lee HJ, Moon YJ, Kim YH, Park C, et al. Systematic analysis of anatomy virtual reality (VR) apps for advanced education and further applications. Sci Rep. 2024 Dec 30;14(1):31835.
3. An GJ. An integrative review on cadaver practice among undergraduate nursing students. J Korean Biol Nurs Sci. 2023 Feb 24;25(1):8–19.
4. Gorbaty B, Arango S, Buyck D, James RC, Porter ST, Iaizzo P, et al. Virtual Reality–based Methods for Training Novice Electrophysiology Trainees—A Pilot Study. J Innov Card Rhythm Manag. 2023 Sep 15;14(9):5583–99.
5. (PDF) Virtual reality and cardiac anatomy: Exploring immersive three-dimensional cardiac imaging, a pilot study in undergraduate medical anatomy education. ResearchGate [Internet]. 2024 Dec 7 [cited 2025 Feb 4]; Available from: https://www.researchgate.net/publication/328145211_Virtual_reality_and_cardiac_anatomy_Exploring_immersive_three-dimensional_cardiac_imaging_a_pilot_study_in_undergraduate_medical_anatomy_education
6. Buyck D, Gherciuc S, Gorbaty B, Escudero EV, Arango S, Perry T, et al. Virtual and Augmented Realities for Cardiac Education and Device Training. In: Iaizzo PA, editor. Handbook of Cardiac Anatomy, Physiology, and Devices [Internet]. Cham: Springer Nature Switzerland; 2024 [cited 2025 Feb 4]. p. 967–81. Available from: https://doi.org/10.1007/978-3-031-72581-4_48
7. Al-Hor M, Almahdi H, Al-Theyab M, Mustafa AG, Seed Ahmed M, Zaqout S. Exploring student perceptions on virtual reality in anatomy education: insights on enjoyment, effectiveness, and preferences. BMC Med Educ. 2024 Dec 2;24(1):1405.
8. Granger NA. Dissection laboratory is vital to medical gross anatomy education. Anat Rec B New Anat. 2004;281B(1):6–8.
9. Korf HW, Wicht H, Snipes RL, Timmermans JP, Paulsen F, Rune G, et al. The dissection course – necessary and indispensable for teaching anatomy to medical students. Ann Anat - Anat Anz. 2008 Feb 28;190(1):16–22.
10. Parker LM. Anatomical dissection: Why are we cutting it out? Dissection in undergraduate teaching. ANZ J Surg. 2002;72(12):910–2.
11. Evans EJ, Fitzgibbon GH. The dissecting room: Reactions of first year medical students. Clin Anat. 1992;5(4):311–20.
12. Finkelstein P, Mathers LH. Post-traumatic stress among medical students in the anatomy dissection laboratory. Clin Anat. 1990;3(3):219–26.
13. Curran VR, Xu X, Aydin MY, Meruvia-Pastor O. Use of Extended Reality in Medical Education: An Integrative Review. Med Sci Educ. 2022 Dec 19;33(1):275–86.
14. Logeswaran A, Munsch C, Chong YJ, Ralph N, McCrossnan J. The role of extended reality technology in healthcare education: Towards a learner-centred approach. Future Healthc J. 2021

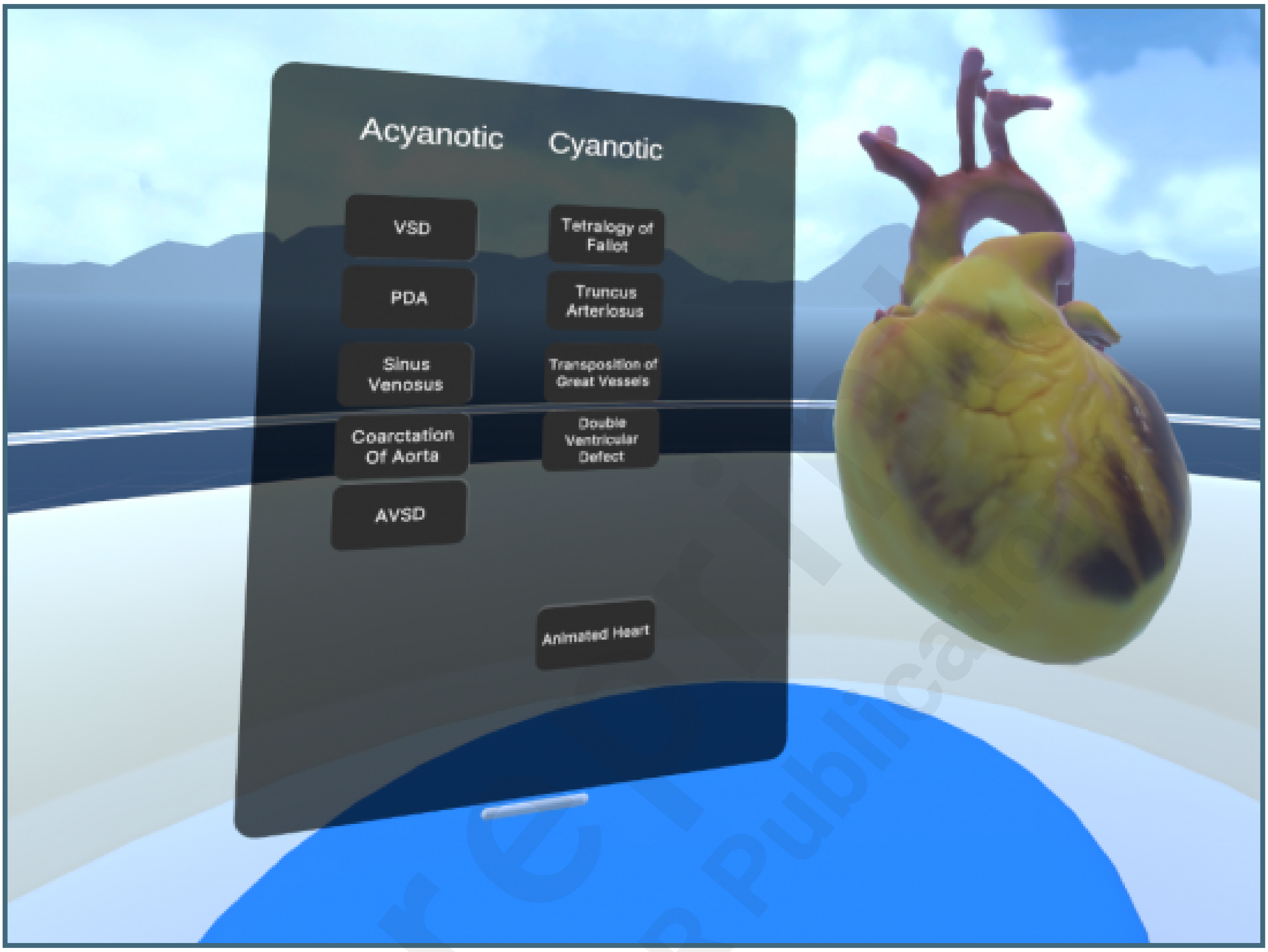
Mar;8(1):e79–84.
15. Kye B, Han N, Kim E, Park Y, Jo S. Educational applications of metaverse: possibilities and limitations. J Educ Eval Health Prof. 2021 Dec 13;18:32.
16. Han HW. A Study on Typology of Virtual World and its Development in Metaverse. J Digit Contents Soc. 2008;9(2):317–23.
17. MILGRAM P, KISHINO F. A Taxonomy of Mixed Reality Visual Displays. 1994 Dec [cited 2025 Feb 4]; Available from: https://search.ieice.org/bin/summary.php?id=e77-d_12_1321
18. Bailenson JN. Virtual Reality. Open Encycl Cogn Sci [Internet]. 2024 Jul 24 [cited 2025 Feb 4]; Available from: https://oecs.mit.edu/pub/2vci5sg1/release/1
19. Son H, Ross A, Mendoza-Tirado E, Lee LJ. Virtual Reality in Clinical Practice and Research: Viewpoint on Novel Applications for Nursing. JMIR Nurs. 2022 Mar 16;5(1):e34036.
20. van der Kruk SR, Zielinski R, MacDougall H, Hughes-Barton D, Gunn KM. Virtual reality as a patient education tool in healthcare: A scoping review. Patient Educ Couns. 2022 Jul 1;105(7):1928–42.
21. Kye B, Han N, Kim E, Park Y, Jo S. Educational applications of metaverse: possibilities and limitations. J Educ Eval Health Prof. 2021 Dec 13;18:32.
22. Seslar SP, Arango S, Buyck D, Ryan james, Iaizzo PA, Deshmukh AJ, et al. A PILOT STUDY COMPARING A CONVENTIONAL SLIDESHOW APPROACH WITH VIRTUAL REALITY FOR TEACHING CARDIAC ANATOMY TO ELECTROPHYSIOLOGY TRAINEES. Cardiovasc Digit Health J. 2022 Aug 1;3(4, Supplement):S13.
23. Arango S, Gorbaty B, Buyck D, Johnson J, Porter ST, Iaizzo PA, et al. A Free-Access Online Interactive Simulator to Enhance Perioperative Transesophageal Echocardiography Training Using a High-Fidelity Human Heart 3D Model. J Cardiothorac Vasc Anesth. 2023 Feb 1;37(2):308–13.
24. Iaizzo P. University of Minnesota. 2025. Free Educational Tools. Available from: https://med.umn.edu/vhlab/research/resources
25. Iaizzo PA, editor. Handbook of Cardiac Anatomy, Physiology, and Devices [Internet]. Cham: Springer Nature Switzerland; 2024 [cited 2025 Feb 4]. Available from: https://link.springer.com/10.1007/978-3-031-72581-4
26. Minouei MA, Omid A, Mirzaie A, Mahdavifard H, Rahimi A. Effectiveness of virtual reality on medical students' academic achievement in anatomy: systematic review. BMC Med Educ. 2024 Dec 2;24(1):1407.
27. Liu K, Zhang W, Li W, Wang T, Zheng Y. Effectiveness of virtual reality in nursing education: a systematic review and meta-analysis. BMC Med Educ. 2023 Sep 28;23(1):710.
28. Baek SW, Yeo T, Lee HJ, Moon YJ, Kim YH, Park C, et al. Systematic analysis of anatomy virtual reality (VR) apps for advanced education and further applications. Sci Rep. 2024 Dec 30;14:31835.
29. Chauhan P, Mehra S, Pandya A. Randomised controlled trial: role of virtual interactive 3-dimensional models in anatomical and medical education. J Vis Commun Med. 2024 Jan;47(1):39–45.
30. García-Robles P, Cortés-Pérez I, Nieto-Escámez FA, García-López H, Obrero-Gaitán E, Osuna-Pérez MC. Immersive virtual reality and augmented reality in anatomy education: A systematic review and meta-analysis. Anat Sci Educ. 2024;17(3):514–28.
31. Salimi S, Asgari Z, Mohammadnejad A, Teimazi A, Bakhtiari M. Efficacy of virtual reality and augmented reality in anatomy education: A systematic review and meta-analysis. Anat Sci Educ. 2024 Dec;17(9):1668–85.
32. Liao ML, Yeh CC, Lue JH, Chang MF. Implementing virtual reality technology to teach medical college systemic anatomy: A pilot study. Anat Sci Educ. 2024 Jun;17(4):796–805.
33. Odame A. Virtual Reality as a Teaching Tool in Cardiac Anatomy Education. [Internet] [Thesis]. [Köthen, Germany]: Anhalt University of Applied Sciences; 2021. Available from:

https://www.hs-anhalt.de/fileadmin/Dateien/FB6/personen/tuemler_j/Master_Thesis_Angela_Odame.pdf
34. Fairén M, Moyés J, Insa E. VR4Health: Personalized teaching and learning anatomy using VR. J Med Syst. 2020;44(5):94.
35. Chheang V, Sharmin S, Marquez-Hernandez R, Patel M, Rajasekaran D, Caulfield G, et al. Towards Anatomy Education with Generative AI-based Virtual Assistants in Immersive Virtual Reality Environments [Internet]. arXiv; 2023 [cited 2025 Feb 5]. Available from: https://arxiv.org/abs/2306.17278
36. Simón-Vicente L, Rodríguez-Cano S, Delgado-Benito V, Ausín-Villaverde V, Cubo Delgado E. Cybersickness. A systematic literature review of adverse effects related to virtual reality. Neurologia. 2024 Oct;39(8):701–9.

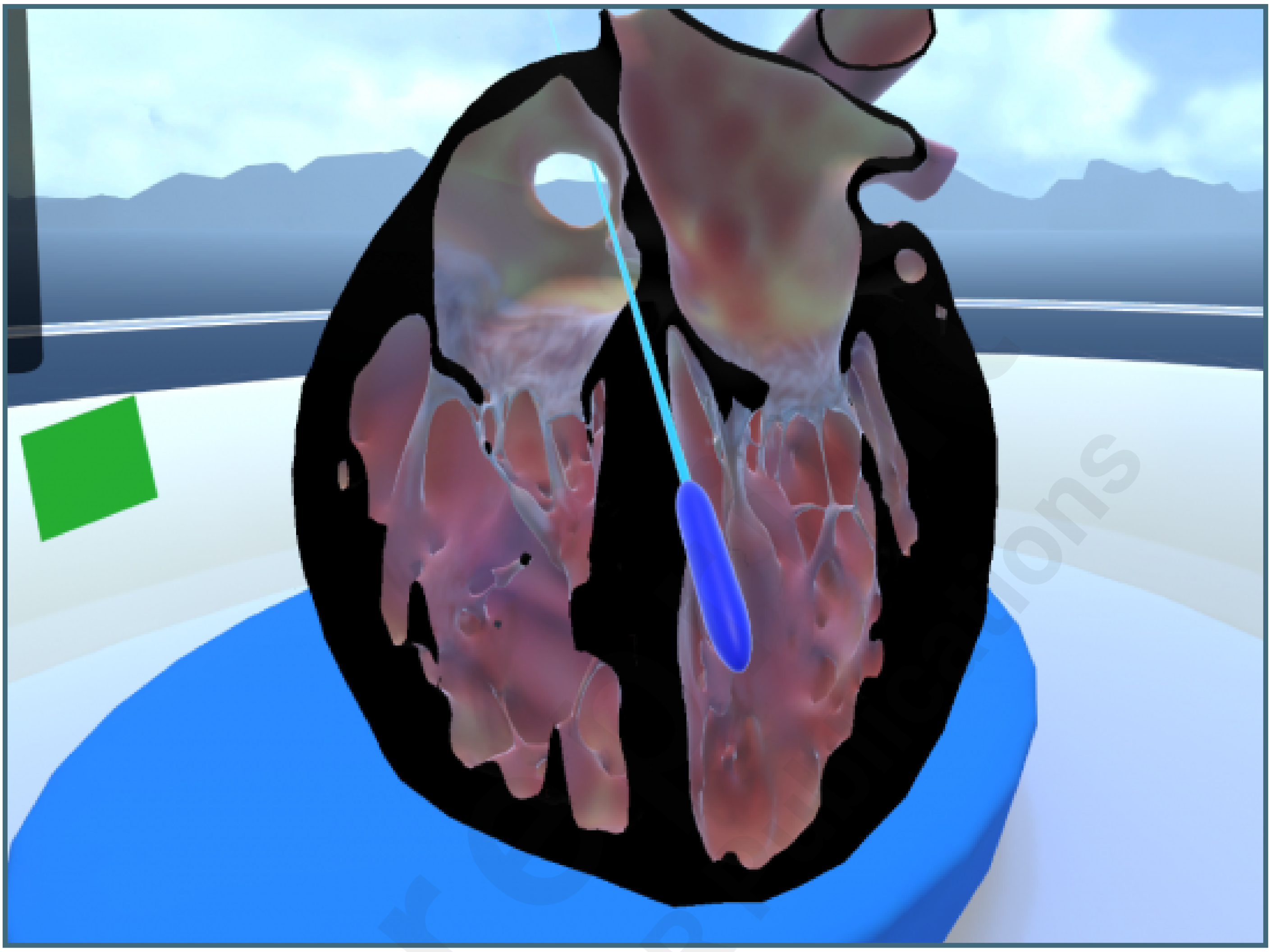
Supplementary Files

Figures

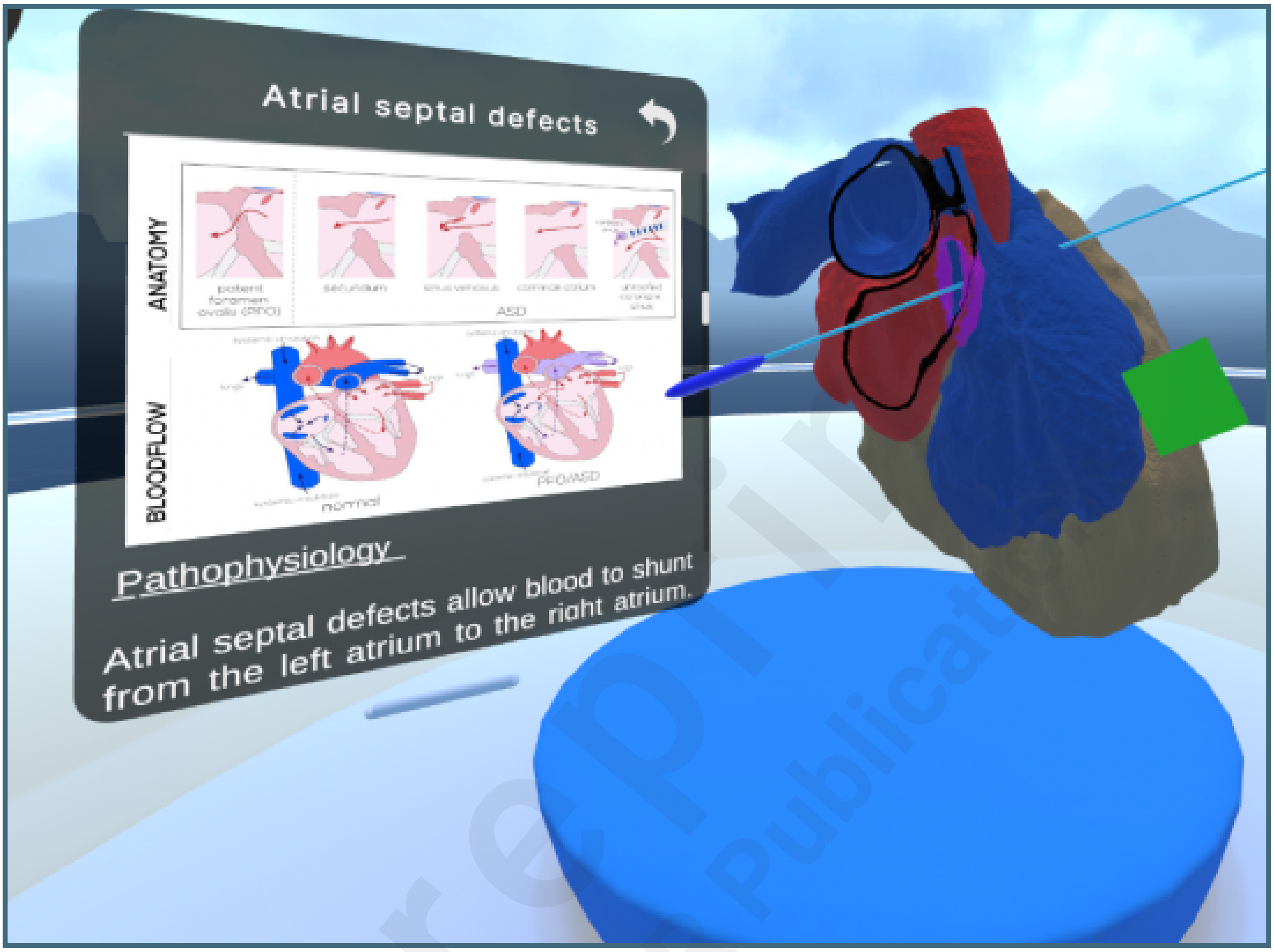
Congenital Heart Defects floating menu with animated normal heart.



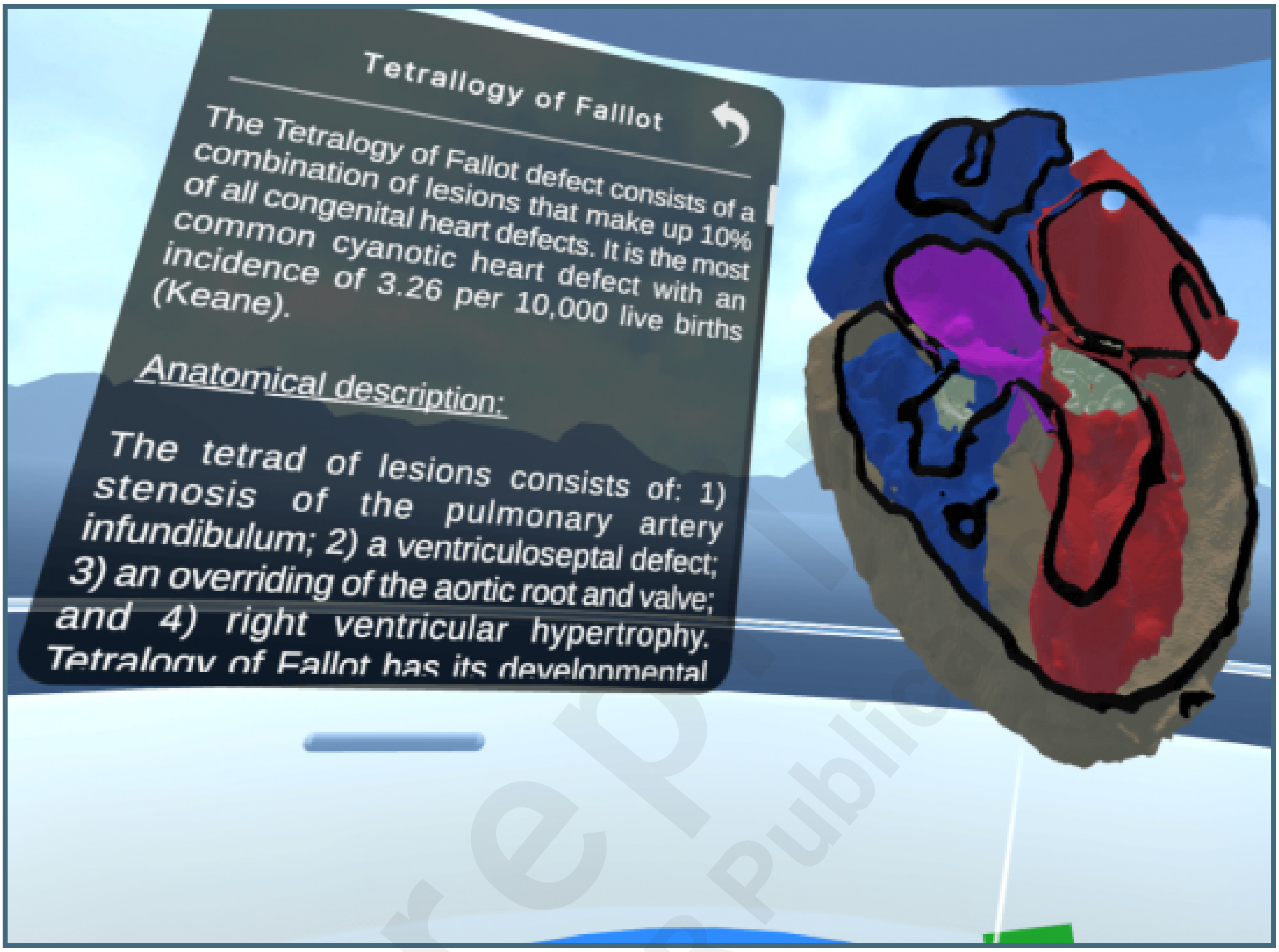
Pointer and plane cutting VR tools.



Atrial Septal Defect (Type Sinus venosus) heart model.



Tetralogy of Fallot heart model.



Collaborative multiplayer environment.