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Enhancing students´ understanding of cardiac physiology by using 4D visualization

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Abstract

Difficulties in achieving knowledge about physiology and anatomy of the beating heart highlight the challenges with more traditional pedagogical methods. Recent research regarding anatomy education has mainly focused on digital three-dimensional models. However, these pedagogical improvements may not be entirely applicable to cardiac anatomy and physiology due to the multidimensional complexity with moving anatomy and complex blood flow. The aim of this study was therefore to evaluate whether high quality time-resolved anatomical images combined with realistic blood flow simulations improve the understanding of cardiac structures and function. Three time-resolved datasets were acquired using time-resolved computed tomography and blood flow was computed using Computational Fluid Dynamics. The anatomical and blood flow information was combined and interactively visualized using volume rendering on an advanced stereo projection system. The setup was tested in interactive lectures for medical students. Ninety-seven students participated. Summative assessment of examinations showed significantly improved mean score (18.1 ± 4.5 vs 20.3 ± 4.9, $p = 0.002$). This improvement was driven by knowledge regarding myocardial hypertrophy and pressure–velocity differences over a stenotic valve. Additionally, a supplementary formative assessment showed significantly more agreeing answers than disagreeing answers ($p < 0.001$) when the participants subjectively evaluated the contribution of the visualizations to their education and knowledge. In conclusion, the use of simultaneous visualization of time-resolved anatomy data and simulated blood flow improved medical students' results, with a particular effect on understanding of cardiac physiology and these simulations may be useful educational tools for teaching complex anatomical and physiological concepts.

KEYWORDS
4D CT, blood flow simulations, cardiac physiology, computational fluid dynamics, medical education

1 | INTRODUCTION

An understanding of the anatomy and physiology of the heart is required for clinical evaluation of cardiac disease (van Dam et al., 2021) and is an integral part of medical program curricula. However, the heart has advanced anatomical structures, intricate spatial relationships, and complex three-dimensional temporal varying structure that may lead to several teaching challenges (Andersson & Loukas, 2009; Mori et al., 2019). Traditionally, human anatomy has been studied using books, lectures, and cadaver dissections but research in the late nineties highlighted difficulties with these traditional methods (Cottam, 1999; Miller, 2000; Garg et al., 2001). Cadaver dissections contribute with a spatial perspective but are limited by ethical considerations and low availability, and do not capture the behavior of the heart over the cardiac cycle. A recent meta-analysis showed that when traditional dissections were compared to other laboratory approaches, i.e., 3D models, digital media, and hybrid approaches, the students' scores were statistically equivalent (Wilson et al., 2018).

In the last 20 years, much of the research in anatomy education has focused on digital three-dimensional models of real anatomy (Yammine & Violato, 2015). Image material for these models is typically acquired from either computed tomography (CT) or magnetic resonance imaging (MRI). The 3D data volumes, acquired by these imaging approaches, are typically visualized using volume rendering, which in modern medical imaging software enables interactive rotation, cross sections, and tissue highlighting. These visualizations can be used in various education settings e.g., as lecture tools or in own computers (Erolin, 2019; Keenan & Awadh, 2019). The procedure where a student or physician interactively can remove and highlight different tissues in reconstructed radiology image datasets is commonly referred to as virtual dissection and has been shown to provide medical students with better preparation for their future clinical work (Darras et al., 2019). There are nowadays also dedicated commercial solutions for interactive visualization of 3D CT and MRI imaging data using e.g., touchscreens and holographic visualizations.

Unlike several other organs in the body, e.g., the brain or skeletal system, the heart has both a complex movement pattern as well as multifaceted intracardiac blood flow patterns. Pedagogical improvements in teaching anatomy using three-dimensional visualization may therefore not be sufficient for cardiac anatomy and its association with physiology. To tackle the pedagogical challenge of describing complex anatomical structures in motion as well as their physiological significance, further development in imaging and visualization techniques may be needed.

MRI allows the acquisition of high quality cardiac 4D anatomical and functional data. Therefore, it may help alleviate the educational difficulties with moving anatomy. However, it is difficult to obtain 4D MRI data with good contrast between blood and myocardium over the whole cardiac cycle. Data is therefore typically acquired as a stack of 2D slices, obtained during different breath holds which impairs spatial resolution and frequently results in misalignments between the slices (Markl et al., 2012). On the contrary, CT enables better contrast levels and a higher resolution. Spiral 3D CT data can be obtained over the whole cardiac cycle in one breath hold and thereby enable 4D rendering of moving structures with both good resolution and contrast levels (Bruns et al., 2022). The combination of sharp contrast levels and defined structures confers an advantage of 4D CT over 4D MRI for understanding and teaching moving anatomy.

For blood flow, however, the arguments are not as clear. MRI allows for measurement and visualization of complex cardiac blood flow patterns within a 3D volume over the cardiac cycle, commonly referred to as 4D flow MRI (Dyverfeldt et al., 2015). Cardiac 4D CT is not able to directly measure intracardiac blood flow. However, the high resolution of CT enables the use of numerical models to calculate the intracardiac blood flow field, commonly referred to as computational fluid dynamics (CFD) (Lantz et al., 2016). Patient-specific blood flow simulations calculated from CT-data have been shown to be qualitatively like 4D flow MRI (Lantz et al., 2018).

Comprehensive visualization of both cardiac anatomy and blood flow is challenging. Commercial visualization solutions dedicated to educational applications are typically limited to 3D visualization, and do not support visualization of motions over the cardiac cycle. Visualization solutions that allow for 4D depiction are available for research and clinical applications but are often too complex for educational use and/or would not allow for simultaneous visualization of blood flow dynamics. Consequently, there is limited research on whether these imaging techniques could be beneficial in medical education. A small study evaluated the use of 4D CT data of the thoracic organs as well as 4D flow MRI and concluded these beneficial and contributory to medical education (Silén et al., 2008). Anatomy was visualized using volume rendering of 4D CT data and blood flow by visualizing 4D flow MRI in a different software tool, with 2D anatomy images as background. This setup might impair understanding of the interplay between anatomy and blood flow and complicates educational usage. Recently, it was shown that it is feasible to integrate CFD and CT data in the same data format, which could facilitate simultaneous visualization of anatomy and blood flow (Temor et al., 2022), even though, in this approach, the anatomy and blood flow information was still stored in separate files and this approach was not evaluated for pedagogical application.

The aim of the current study was therefore to evaluate whether simultaneous interactive stereo visualization of 4D CT-based anatomy and blood flow simulations can improve medical students' knowledge regarding cardiac structure and function.

2 | MATERIALS AND METHODS

2.1 | Simultaneous 4D visualization of anatomy and blood flow

Three cardiac 4D CT datasets were selected for the study. One dataset was without known pathology (H1), one with a clinically severe aortic stenosis (H2), and one with dilated cardiomyopathy (H3). The image data for this study was collected during clinical routine and use for research was approved by the Swedish Ethics Review Authority, regional committee Linköping (dnr: 2017/502-31). The data was pseudonymized before image export.

All datasets were acquired by using a third-generation dual-source CT scanner (*Somatom Force; Siemens Healthineers, Erlangen, Germany*). The images were acquired in spiral mode during inspiratory breath holds. Multiphase image reconstructions were generated, including phases at every 5% between two R-R intervals from 0% to 100% (20 phases). The atria and ventricles of the acquired data sets were segmented semi-automatically using Medviso CT Segment (*Lund, Sweden*) (Heiberg et al., 2010) and ITK-SNAP 3.8 (*Pennsylvania/Utah, United States*) (Yushkevich et al., 2006). For the dataset without pathology (H1) both the right and the left sides were segmented whilst only the left side was segmented for the pathological datasets (H2 and H3). SpaceClaim (*Ansys Inc., Canonsburg, PA*), was used to cut

FIGURE 1 Calculated flow simulation. This image was exported from the data set without known pathology (H1) at peak systole.

the veins and arteries to close the volume. A registration algorithm was applied to track the wall motion over time. The flow was computed using CFX 17.0 (*Ansys Inc., Canonsburg, PA*) and Fluent 2019R1 (*Ansys Inc., Canonsburg, PA*). An exported image from the calculated flow simulation is presented in Figure 1.

To combine the 4D CT data with the functional velocity data from CFD, CT Hounsfield values for voxels inside the blood pool were replaced with the magnitude of the velocity. The velocity data was encoded using linearly scaled velocity values, where 1000 represented absolute velocities of 0 m/s and 3000 represented 6 m/s. As Hounsfield units above 1000 are not present in the heart, besides in potential metal implants, this allowed volume rendering visualization of the velocity data without interfering with anatomical information in the dataset. The resulting images were exported as a sequence of single slice DICOM files, the same file format as the original data, for compatibility with the utilized hardware.

The integrated data sets were transferred to a Siemens LEONARDO® workstation (*Siemens Healthineers, Erlangen, Germany*), which enabled volume rendering and projection of the 4D, real time, image data. The workstation was connected to 6P RGB laser projector (DP4K-30 L 6P Laser projector, Barco, Belgium) projected to a 3.9 by 2.1 m laser coated glass screen which enabled virtual reality (VR) 3D visualization with a resolution of 4096*2160 px using stereoscopic glasses (Barco 3D, Dolby Laboratories, San Francisco). Optimal stereoscopic depiction was achieved by an in-house modification of the software in the LEONARDO system.

Several volume rendering parameter presets were manually and individually created for the three datasets with the ability to shift between 3D anatomy, 4D anatomy and 4D anatomy with flow simulations. The anatomy and velocity were visualized by creating transfer functions. The anatomical information was visualized in gray scale where denser tissues were projected as a lighter gray color and less dense tissues as a darker gray color. The velocity data was visualized with different colors depending on different velocity ranges (Blue: 0–0.3 m/s, Red: 0.2–1.3 m/s, and Yellow: 1.2–6 m/s). An example of a preset and transfer function is shown in Figure 2. An exported image from the simultaneous visualization is shown in Figure 3 and recordings of the time-resolved images is shown in supplementary material S1 and S2.

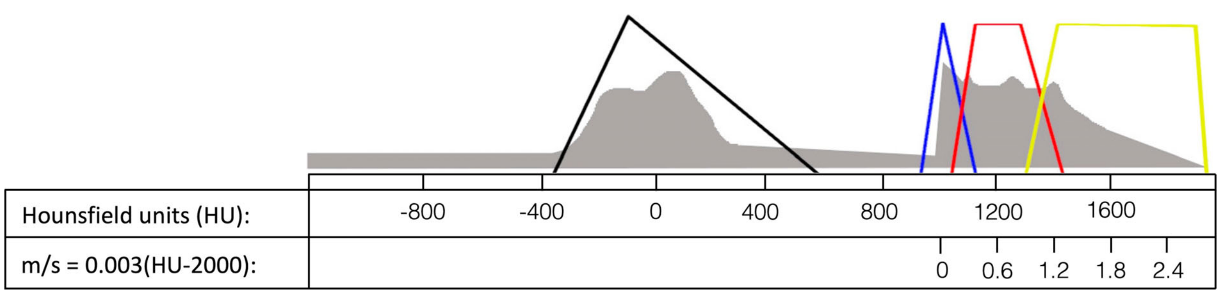

FIGURE 2 Example of a preset and transfer function in Hounsfield units (HU) and velocity (m/s). The black line defines the range for visualized anatomy in gray scale color. Velocity ranges visualized with three colors. The levels in this figure were extracted from the dataset without known pathology (H1).

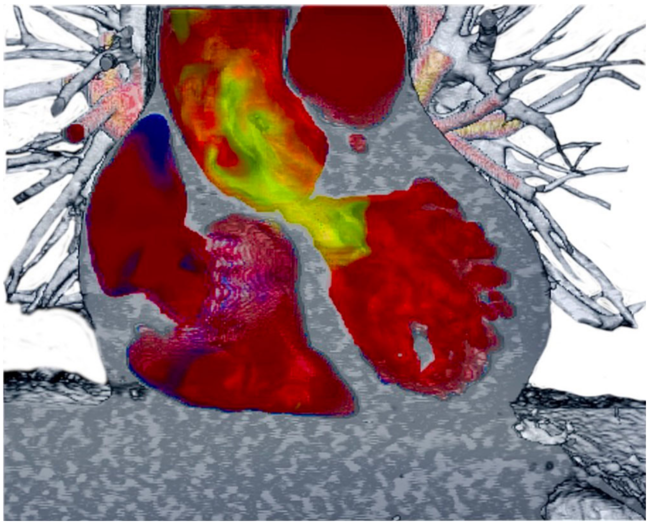

FIGURE 3 Visualization of merged CT and CFD data. This image was exported from the dataset without known pathology (H1) at mid systole.

2.2 | Pedagogic assessment

The pedagogical assessment of the 4D anatomical and blood flow visualization took place at the medical program at Linköping University. First year medical students ($n = 110$) were invited to participate. The students were randomly divided into four groups (A, B, C and D) to enable better possibilities for interactive lectures and to fit in the advanced lecture room.

Two course objectives from the medical school curriculum were selected for assessment:

- Structure and main functions of the circulatory and respiratory systems.
- Physiological processes that regulate and affect cardiac work, pressure/volume, blood pressure and blood flow.

The current project was chronologically scheduled after all available lectures and learning elements regarding the two selected course objectives, but the students had not been examined yet. This was intentional to ensure that any potential effect on knowledge could be linked to the 4D simulations.

Two experienced assistant teachers (X and Y, both senior medical students) were selected to teach in the project. The two teachers had prior experience in teaching cardiac anatomy and physiology with traditional pedagogical methods, e.g., cadaver dissections and lectures, for pre-clinical medical students. The teachers were given access to and technical support for the 4D simulations and had the opportunity to be accustomed to them a week before the scheduled lecture times. The teachers were instructed to separately construct an interactive lecture, with the visualizations as a pedagogical aid, regarding the two selected course objectives. The lecture time was 70 minutes, and the participating students did not have access to phones or computers, or the possibility to take notes during the lecture. The teachers were blinded to the research questions during the whole project. Teacher X was randomly assigned to group A and B while Teacher Y was assigned to group C and D.

TABLE 1 Description of question areas

Question area:	Regarding knowledge:	Maximum score:
Q1:	Anatomical area of blood supply for each coronary artery.	3
Q2:	Differences in the ratio between ventricular volume and myocardial wall mass in eccentric and concentric hypertrophy.	4
Q3:	The physiological meaning of the ECG waves.	4
Q4:	Cardiac output during exercise.	4
Q5:	The heart valves corresponding landmarks in heart auscultation.	4
Q6:	Changes in the heart function due to aging.	4
Q7:	Pressure and velocity differences between the left ventricle and the aorta in a heart with a narrowed aortic valve.	4
Q8:	The physiological reason behind the third heart sound (S3) in cardiac auscultation.	1

Note: Description of the content (middle column) in each question area (Q1-Q8) (left column) addressed in the exam as well as the maximum score of each area (right column).

A written examination was used to identify specific pedagogic strengths of the 4D visualizations. The exam was produced in collaboration with four professors with different clinical disciplines of cardiology, clinical physiology, radiology, and physiological measurements. All four had prior experience with writing examination questions for similar course objectives. The participants completed the examination individually, without any help tool, and immediately before (*pre-exam*), and after (*post-exam*) the lecture in the lecture room. The two exams were identical, but the participants were not informed of this until after the lecture to avoid direct questions about its content. The exam was divided into eight different Question Areas (Q1-Q8), each containing several questions regarding the same subject-matter. See description of each Question Area in Table 1. The questions were either of a "multiple-choice" or "true or false" character to facilitate statistical analysis. The maximum score of the exam was 28. Neither of the teachers had access to or knowledge of the questions or content of the exams.

For formative assessment, a supplementary evaluation form was answered by the participants after the lecture. The form contained five statements (E1-E5) with grade answers from 1 to 5. For analysis, 1 and 2 were interpreted as "disagreeing answers", 4 and 5 as "agreeing answers" and grade 3 as "neutral". See description of each evaluation scale in Table 2.

TABLE 2 Description of evaluation scales

Scale number:	Evaluation statement:
E1:	Do you feel more confident regarding the anatomy of the heart? *1: No, not more confident. 5: Yes, much more confident!*
E2:	Do you feel more confident regarding the physiology of the heart? *1: No, not more confident. 5: Yes, much more confident!*
E3:	Were the 3D-glasses important for the learning experience? *1: No, it did not contribute to the learning experience at all. 5: Yes, it did contribute a lot!*
E4:	Did the lecture give you more knowledge than other learning elements? *1: No, it did not add any knowledge. 5: Yes, it gave me a lot more!*
E5:	Do you think the lecture should be implemented in your course in the future? *1: No, I do not think it should be implemented. 5: Yes, I really think it should be implemented!*

Note: Description of each evaluation statement (right column) in each numbered scale (E1-E5) (left column). These evaluation scales formed the evaluation form which the students answered after the lecture.

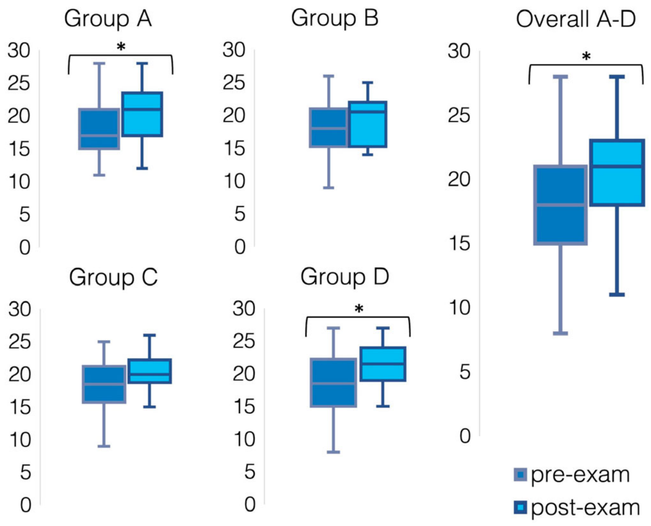

FIGURE 4 Mean score on the y-axis divided on each student group (A–C) and overall (A–D). The two colors of the boxes define pre-exam (lighter blue) and post-exam (darker blue). The maximum score of the exam was 28. **Statistically significant improvement*.

2.3 | Statistical considerations

Examination results are given as mean score (±standard deviation) for pre- and post-examination as well as the percentage improvement. The intergroup comparisons were statically evaluated with paired t-tests. Comparisons between the two teachers are given as mean percentage improvement and are based on the mean score (±standard deviation) within respectively student group presented above. Comparisons of improvement divided by Question Areas are given in percentage correct answers and were statically evaluated with paired t-tests. Results from the formative assessment are given as distribution between answers and the proportion between agreeing, disagreeing and neutral answers were statistically evaluated with Chi-square test of independence. The significance level was set at 5%. All analyses were performed two-sidedly. Statistical analyses were performed using Excel, version 16.59 (Microsoft, Redmond, WA).

3 | RESULTS

Out of the 110 medical students included, 97 (88%) participated in the voluntary lecture '*Immersion of the anatomy and physiology of the heart by four-dimensional visualization*', as well as the associated assessments.

3.1 | Summative assessment

In an overall comparison (all students), the mean score from the pre-exam to the post-exam improved significantly (18.1 ± 4.5 vs 20.3 ± 4.9 (12.2%), $p = 0.002$). By group analysis showed that Group A and D had statistically significant improved scores (Group A: 17.8 ± 4.3 vs 20.4 ± 4.5 (14.6%) $p = 0.003$; Group D: 18.3 ± 5.1 vs 21.3 ± 4.83 (15.9%) $p = 0.003$). Group B and C improved less and did not reach statistical significance (Group B: 17.9 ± 3.6 vs 19.4 ± 3.9 (8.6%) $p = 0.128$; Group C: 18.5 ± 4.39 vs 20.1 ± 4.92 (8.3%) $p = 0.148$). The mean score and distribution in the pre-exam and post-exam, both overall and divided by student group, are presented in Figure 4.

There was no significant difference in percentage improvement between student groups divided by teacher (X(AB): 11.6% vs Y(CD): 12.1%, $p = 0.924$). Both teachers had one student group with a significant improvement, Group A for teacher X and Group D for teacher Y, and one student group without significant improvement, Group B for Teacher X and Group C for Teacher Y.

Two Question Areas demonstrated significant improvements between pre- and post-exam. The percentage of correct answers within Q2 (hypertrophy) improved from 67% correct answers to 90% ($p < 0.001$) and Q7 (pressure differences over a narrowed valve) improved from 61% correct answers to 80% ($p = 0.001$). The percentage of correct answers within each Question Area (Q1-Q8), pre- and post-exam, are presented in Figure 5.

3.2 | Formative assessment

There was significantly more agreeing (grade 4 and 5) than disagreeing (grade 1 and 2) and neutral (grade 3) answers to the evaluation statements (E1-E5), ($x^2 = 38.9$, $df = 8$, $p < 0.001$). Statement E5 (implementation in future education) displayed the highest level of agreement as well as lowest level of disagreement (84 vs 0). Conversely, statement E1 (confidence in anatomy) displayed least agreement and most disagreement (30 vs 9). The distribution between answers within each evaluation statement is presented in Figure 6.

4 | DISCUSSION

We investigated if simultaneous interactive stereo visualization of 4D CT-based anatomy and blood flow simulations improved medical students' knowledge regarding cardiac structure and function. We found the data mostly contributory to the understanding of physiological and functional aspects. The participating students also evaluated the lecture as strongly contributory to their course and advocated future implementation.

The summative examination covered several aspects regarding the anatomy and physiology of the heart, but the overall improvement was mainly driven by two Question Areas which were both well represented by the selected and visualized data sets. One of these areas contained questions regarding hypertrophy and how the ratio between ventricular volume and myocardial wall mass differs in two distinct types of cardiac remodeling (i.e., eccentric vs. concentric hypertrophy). The other area contained questions regarding pressure differences and blood flow velocity over a narrowed aortic valve. It is interesting that both these areas had a physiological response due to a structural variance. In contrast, the percentage of correct answers to purely anatomical questions such as each coronary artery's area of blood supply or the anatomical landmarks for auscultation, were not significantly improved following the lecture. The lack of improvement in knowledge of the coronary arteries is surprising considering that CT imaging is recommended in suspected coronary artery occlusions according to e.g., European Society of Cardiology (ESC) Guidelines (Knuuti et al., 2020). However, this may indicate that further improvements in achieving learning objectives can be obtained by enhancing the visualization of the coronary arteries specifically.

Lack of improvement in correct responses in the area regarding cardiac output during exercise was also observed. This is possibly explained by the lack of a representative dataset. Therefore, it would be interesting for future studies to include datasets during stress or recent exercise, and anew evaluate if this could improve this subject-matter. Similarly, lack of improvement in the area regarding the different ECG curves, may be explained by the lack of representing datasets. It would be interesting to include ECG in future simulations e.g., simultaneous ECG curves in relation to the heartbeat, modeling of cardiac electrophysiology, or inclusion of patients with various cardiac arrythmias in order to explore if a better understanding of ECG can be achieved.

In the formative assessment, the students strongly agreed that the lecture should be included in their course in the future and a substantial number of students stated that they gained more knowledge compared to previous teaching methods in their course. The stereoscopic effect with 3D-glasses was also considered important for the learning experience. Most of the students also stated more confidence regarding both the anatomy and the physiology of the heart, with an advantage for physiology. Consequently, formative assessment results support the validity of the summative assessment by examination questions, where four dimensional images were shown to contribute to understanding physiological and functional concepts.

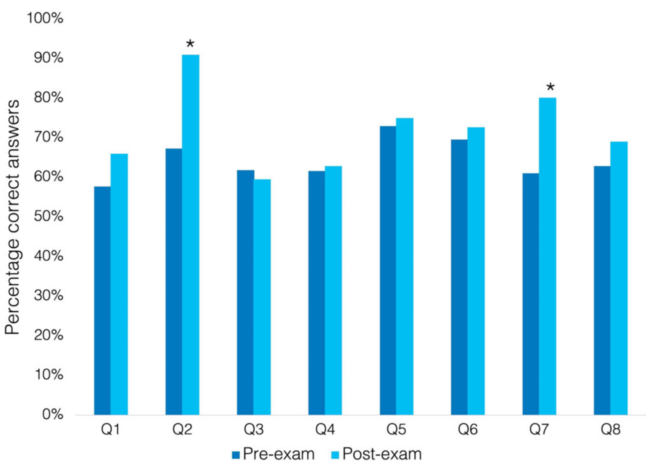

FIGURE 5 Percentage correct answers on the y-axis presented by each question area (Q1-Q8). The pre-exam values are shown in lighter blue and post exam values in lighter blue. **Statistically significant improvement*.

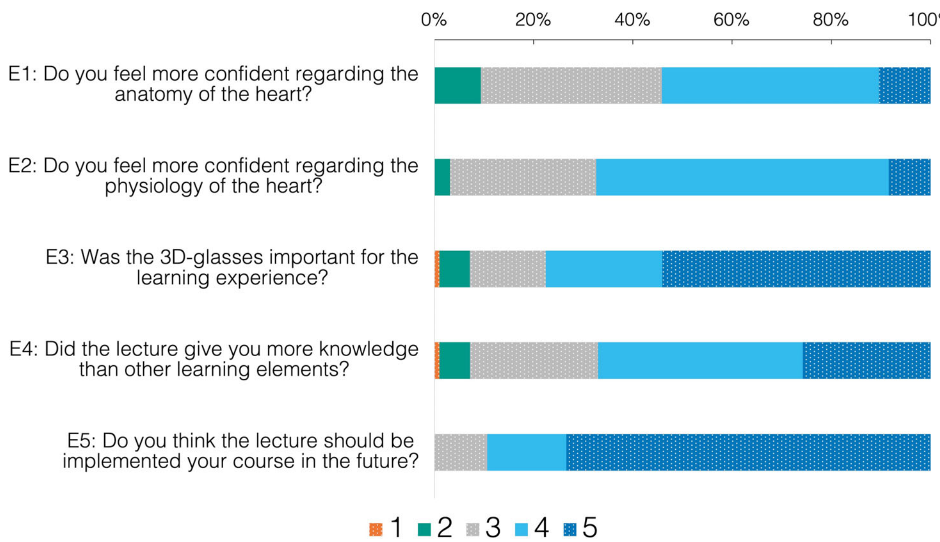

FIGURE 6 Percentage distribution of answers to each evaluation statement (E1-E5) in the summative assessment. The grades (1–5) are presented in different staple colors.

Implementation of anatomy and physiology visualization of the beating heart has been limited by the availability of dedicated user-friendly visualization software. In this study, we simplified this task by combining anatomical and blood flow information in one 4D dataset, which can be visualized using standard 4D volume rendering software. For 4D volume rendering, we used a clinical Siemens LEONARDO® computer, which we adapted to allow for stereoscopic visualization. This solution resulted in reasonable user friendliness for education, but further improvement in user-friendliness is expected to be possible in a dedicated 4D volume rendering software package for educational purposes.

This study has some limitations. The primary limitation is the lack of a control group in the study design. Adding a control group would mean that not all students would have had access to the same educational resources, which was not preferred. Future studies should preferably include a control group and assess long term follow-up to be able to assess the impact on actual course examinations and retention of knowledge. One further limitation is the relative few selected datasets with abnormalities. The results are highlighting an increased understanding of the representative datasets but including more datasets with cardiac abnormalities may lead to further enhancement of the understanding of cardiac pathophysiology. Also, further improvements in the interactive visualization, which normally comes with increased user experience, is expected to improve the outcome further for, e.g., coronary anatomy.

Nonetheless, the current study clearly shows the potential of these advanced visualizations for pedagogical applications. In this study, we chose to perform the visualizations in a lecture room using an advanced VR theater. For small group education, a similar solution could probably be used in combination with Virtual Reality glasses or further developed visualization tables, which also give a good 3D understanding. This may also enable a higher grade of interactivity, something that previous research has showed contributory to anatomy education.

In conclusion, the use of simultaneous visualization of 4D CT data and simulated blood flow improved medical students' results in summative assessments, supported by formative assessment, indicating a significant effect particularly on understanding of cardiac physiology. 4D simulations may be a useful educational tool for teaching complex anatomical and physiological concepts.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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