Original Research Paper

Application of virtual reality and augmented reality technologies in clinical teaching of cardiac surgery

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Abstract

Cardiac surgery training faces a number of challenges due to procedural complexity and limited hands-on opportunities. This study evaluated the effectiveness of a self-developed Virtual Reality (VR)-based training system compared to traditional teaching methods in developing the surgical skills and clinical knowledge of medical students during their cardiac surgery rotation. A single-center, parallel-group randomized controlled trial was conducted from September 2023 to June 2024. Of 123 eligible fifth-year medical students, 60 were stratified by age, gender, and prior grade point average and randomly assigned equally to an experimental group (VR-based training) or a control group (conventional teaching). The VR system provided immersive simulation of coronary artery bypass grafting, valve replacement/repair, and atrial septal defect repair. Outcome measures included surgical skills, total clinical assessment score, learning interest, self-practice time, teacher evaluations, and system acceptance. Data were analyzed using t-tests, chi-square tests, and Pearson correlation. The experimental group significantly outperformed the control group in surgical operation skills (36.5 ± 2.5 vs. 32.1 ± 3.0, P<0.001) and total clinical assessment score (90.6 ± 5.0 vs. 84.5 ± 5.5, P<0.001). Subjective evaluations showed significantly higher learning interest (4.73 ± 0.15 vs. 3.11 ± 0.66, P<0.001), immersion and engagement (4.72 ± 0.29 vs. 2.90 ± 0.82, P<0.001), and weekly self-practice time (66.8 ± 2.1 vs. 58.3 ± 4.5 minutes, P<0.001) in the VR group. Teacher ratings of clinical thinking, self-directed learning, teamwork, and interest stimulation were also significantly higher for the experimental group (all P<0.05) and correlated positively with assessment scores (r=0.72–0.84, P<0.001). In this single-center randomized trial, a self-designed VR cardiac surgery training system improved medical students' operative skills, clinical knowledge, and learning engagement compared to traditional methods. These findings provide encouraging evidence supporting VR as a promising pedagogical adjunct in cardiac surgery training, though further large-scale multi-center studies are needed to confirm its effectiveness.

Keywords: Virtual reality, cardiac surgical procedures, clinical competence, education, medical

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BACKGROUND

Cardiovascular surgery is a medical specialty with high technical complexity, significant operative risk, and a lengthy learning curve. The traditional apprenticeship-based model, reliant on observation and limited hands-on practice, is often inefficient and may fail to provide undergraduate medical students with adequate exposure to the core concepts of complex surgical procedures during their clinical rotations. The rise of minimally invasive techniques has further reduced opportunities for direct observation.[1] A significant challenge persists across global healthcare systems: improving the efficiency, effectiveness, and accessibility of surgical skill acquisition without compromising quality or escalating costs.[2]

In China, undergraduate medical education follows a nationally standardized clinical internship system, in which fifth-year medical students complete mandatory rotations across multiple specialties, including cardiovascular surgery. This rotation represents the first systematic clinical exposure for medical students and serves as a critical period for shaping their professional interests and career trajectories. Therefore, implementing more effective and engaging teaching methods to enhance the quality of cardiovascular surgery rotations can not only cultivate graduates with solid clinical competencies, but also potentially attract more talented students to this demanding—yet critically understaffed—specialty. Wuhan Union Hospital where this study was conducted, is a tertiary academic medical center performing approximately 7,000 cardiovascular surgeries annually, with an established clinical education system. This setting provided a structured environment for implementing and evaluating novel teaching techniques.

Virtual Reality (VR) is such a novel teaching technique that offers promising solutions by creating immersive, interactive simulated environments.[3,4] Its application in surgical training can provide risk-free, repeatable practice and enhance spatial understanding of complex anatomy.[5] Global market analyses predict significant growth for VR in surgical education.[6] Supported by national initiatives in many countries, VR platforms are emerging across various surgical disciplines.[7-10]

Previous studies have demonstrated benefits of VR in neurosurgical, urological, and general surgical training, including improved spatial understanding and skill acquisition.[3,4,7-10] However, dedicated systems in cardiovascular surgery have developed relatively slowly due to procedural complexity, thus a widely adopted, validated system is currently lacking. Most existing studies lack rigorous randomized controlled designs or objective skill-based outcome measures in cardiac surgery contexts. This study aimed to develop a specialized VR-based cardiac surgery teaching platform through interdisciplinary collaboration, and to evaluate its efficacy against traditional teaching methods in a randomized controlled trial.

METHODS

2.1 Study Design and Setting

This single-center, parallel-group randomized controlled trial was conducted at Union Hospital, Tongji Medical College, Huazhong University of Science and Technology, Wuhan, China, from September 2023 to June 2024.

The cardiovascular surgery rotation is a mandatory clerkship for fifth-year medical students at our hospital. The final assessment score accounts for approximately 10% of the overall rotation grade. During the study period, students concurrently rotated through other clinical departments; however, the cardiovascular surgery module was conducted as an independent block with dedicated teaching activities and assessments. The rotation assessment constitutes one component of the overall clinical competence evaluation and does not solely determine students' graduation outcomes, which mitigates concerns about fairness in comparing different teaching methods.

2.2 Participants

A total of 123 fifth-year clinical medicine students undergoing clinical internships in the Department of Cardiovascular Surgery were assessed for eligibility. Students with prior VR experience in surgical simulation were excluded to avoid contamination effects.

To control for potential confounding factors and enhance intergroup comparability, eligible participants were stratified based on age, gender, and prior comprehensive Grade Point Average (GPA) from the first three academic years. Within each stratum, computer-generated random numbers were used to allocate students in a 1:1 ratio to two groups: the Experimental Group (VR teaching, n=30) and the Control Group (conventional teaching, n=30). Randomization was performed by an independent statistician. Baseline characteristics including age, gender, and prior GPA showed no statistically significant differences ($P > 0.05$).

2.3 Interventions and Comparisons

Experimental Group Intervention: Students received VR-based training in addition to routine ward duties. The hardware platform consisted of the PICO® Ultra 4 head-mounted display system equipped with six-degree-of-freedom wide-frequency vibration controllers featuring infrared optical tracking. Software utilized the EVDO 2.2.9 three-dimensional anatomical dataset from the

"YiWeiDu Virtual Simulation Medical Platform," supporting tissue transparency adjustment, cross-sectional imaging, and color-coding of arterial and venous systems. Data models were integrated into the PICO® Developer Platform (PicoMRTK3) for interactive script development. A patented VR cardiac surgery simulation method (CN201910566776.2) provides technical foundation for our system.[11]

The curriculum included three procedures: Coronary Artery Bypass Grafting (CABG); Valve Replacement or Repair; and Atrial Septal Defect (ASD) Repair. Insta360 4K panoramic cameras recorded standardized surgical demonstrations. Post-processed videos were integrated into the Unity3D 2023 engine using multi-camera spatiotemporal synchronization algorithms to generate seamless panoramic videos.

Students interacted with virtual three-dimensional heart models via controllers for rotation, zooming, cross-sectional cutting, and exposure. The system enabled real-time commentary during surgical playback and could be combined with a self-made box-type cardiovascular surgery simulator to replicate real intraoperative scenes. Choice options at key surgical steps assessed decision-making regarding surgical approach, instrument selection, and management of special situations. Students completed at least one simulated surgery or anatomy learning course per working day, accumulating minimum requirements of 10 simulated valve surgeries, 10 ASD surgeries, and 10 CABG procedures.

Control Group Intervention: The control group students were informed and agreed that they would not receive VR training during the rotation. They received traditional clinical teaching—participating in cardiovascular surgery team learning and completing a three-month skills training program. This included observation and teaching with equivalent case exposure (10 observed valve surgeries,10 observed ASD surgeries, and 10 CABG training sessions).

All teaching and assessment were conducted by instructors from the Department of Cardiac Surgery at or above Associate Chief Physician level.

2.4 Outcome Measures

Primary Outcomes: (1) Surgical Operation Skills score (out of 40 points), assessed through VR-simulated mitral valve replacement, evaluated by three instructors via double-blind review of operation videos; (2) Total Clinical Assessment score (out of 100 points), comprising Basic Cardiac Surgery Theory (30 points), Cardiac Surgery Surgical Theory (30 points), and Surgical Operation Skills (40 points).

Secondary Outcomes: (1) Subjective learning interest measured by the VR-based Learning Interest Scale (VR-LIS, a five-point Likert scale);[12] (2) Learning engagement measured by immersion and engagement scores; (3) Weekly self-practice time; (4) Teacher evaluations of student performance across four dimensions: clinical thinking, self-directed learning, teamwork, and learning interest stimulation.

2.5 Teaching Effectiveness Evaluation

For Students: Two questionnaires were designed based on Likert methodology:[12] The VR-LIS (Appendix 1), assessing students' cognitive, affective, behavioral, and persistent interest dimensions; and the VR System Acceptance Scale (VR-SAS, Appendix 2), investigating students' experience using the VR operating system. Questionnaires were completed anonymously. All items were scored 1–5 (Strongly Disagree to Strongly Agree). Higher scores indicate higher levels of agreement.

Students completed the teaching evaluation after the rotation; the VR experience questionnaire was completed after first system use. Control group students received a standardized 30-minute orientation (headset operation, controller handling, navigation) before assessment to ensure fair comparison. The assessment tasks were designed to focus on procedural decision-making and basic operative steps rather than requiring complex fine manipulations with the VR controllers.

For Teachers: A questionnaire (Appendix 3) was designed using the same Likert methodology.[12] Teachers (Associate Chief Physicians or higher level from the Department, blinded to group allocation) rated students across the same four domains listed in 2.3. Correlation analysis was performed between these scores and students' total assessment scores to assess the consistency between subjective teacher evaluations and objective performance measures.

2.6 Statistical Analysis

Sample size (n=30 per group) was determined *a priori* using G*Power 3.1 (Heinrich Heine University, Düsseldorf, Germany), assuming a large effect size (Cohen's d=0.8), α=0.05, and power=0.80.

Data were analyzed using SPSS 29.0 (IBM Corp., Armonk, NY, USA). Normality of continuous variables was verified using the Shapiro–Wilk test. Continuous variables are expressed as mean ± SD and compared between groups using independent samples t-tests; categorical variables as frequency (%) and compared using chi-square tests. Effect sizes (Cohen's d) and 95% confidence intervals were calculated for primary outcomes. Pearson correlation assessed associations between teacher evaluations and total scores, with $r \geq 0.8$ considered strong correlation. $P < 0.05$ was considered statistically significant.

RESULTS

3.1 Participant Characteristics

All students in both groups successfully completed the cardiovascular surgery rotation training. In the experimental group, there were 15 males (50.0%) and 15 females (50.0%), with a mean age of 23.5 ± 0.48 years. In the control group, there were 14 males (46.7%) and 16 females (53.3%), with a mean age of 23.5 ± 0.46 years. Students were matched based on comprehensive Grade Point Average from the first to third academic years, with prior scores of 82.4 ± 0.54 and 82.4 ± 0.56, respectively. Baseline characteristics showed no statistically significant differences ($P > 0.05$), indicating good comparability between groups (Table 1).

3.2 Primary Outcomes: Assessment Scores

Regarding theoretical assessment, the experimental group scored slightly higher than the control group in Basic Theory (26.8 ± 2.1 vs. 25.9 ± 2.3, $P = 0.12$) and Surgical Theory (27.3 ± 2.0 vs. 26.5 ± 2.2, $P = 0.15$), but these differences were not statistically significant. However, the experimental group significantly outperformed the control group in Surgical Operation Skills (36.5 ± 2.5 vs. 32.1 ± 3.0, $t = 6.12$, $P < 0.001$, Cohen's d = 1.63) and Total Assessment Score (90.6 ± 5.0 vs. 84.5 ± 5.5, $t = 4.50$, $P < 0.001$, Cohen's d = 1.16) (Table 2).

3.3 Secondary Outcomes: Learning Interest and Engagement

The experimental group scored significantly higher than the control group across all subjective evaluation dimensions (Table 3). The overall clinical learning experience score increased by 8.5% compared to the control group (4.45 ± 0.38 vs. 4.10 ± 0.75, $P = 0.027$). Learning effect and confidence scores increased by 50.8% (4.60 ± 0.32 vs. 3.05 ± 0.68, $P < 0.001$), while immersion and engagement scores increased by 62.8% (4.72 ± 0.29 vs. 2.90 ± 0.82, $P < 0.001$).

Regarding learning behavior, experimental group students spent an average of 7.5 more minutes per week on self-directed theoretical learning (88.5 ± 6.2 vs. 82.3 ± 7.5 minutes, $P = 0.001$) and extended self-practice time for surgical skills by 14.6% (66.8 ± 2.1 vs. 58.3 ± 4.5 minutes, $P < 0.001$). The overall learning interest score reached 4.73 (out of 5), representing a 52.1% increase compared to the control group (3.11 ± 0.66, $P < 0.001$). All four sub-dimensions—cognitive interest (Cohen's d = 3.06), affective interest (d = 3.22), behavioral interest (d = 2.90), and persistent interest (d = 2.68)—showed significant enhancement effects.

3.4 System Acceptance and Technical Evaluation

Questionnaire results showed that 79.3% of students held positive evaluations (Strongly Agree or Agree) of the VR system; 11.3% were neutral; and 9.3% held negative evaluations. The system received high recognition for interactivity (66.7% positive), ease of control (80.0% positive), content comprehensiveness (80.0% positive), and detail presentation (93.3% positive). However, negative feedback focused on visual realism (33.4% non-positive), motion sickness or nausea (20.0% non-positive), and eye discomfort (13.3% non-positive) (Table 4).

3.5 Comparison of Teacher Evaluations

Teachers' ratings for students in the experimental group across four dimensions were all significantly higher than those for the control group (all $P <$

0.05). Specifically, the experimental group scored higher in clinical thinking ability (91.23 ± 3.64 vs. 80.45 ± 5.56, t = 8.98, P < 0.001, Cohen's d = 1.63); self-directed learning ability (89.45 ± 4.48 vs. 82.76 ± 8.31, t = 4.02, P = 0.001, Cohen's d = 0.73); teamwork ability (88.62 ± 3.35 vs. 83.63 ± 4.82, t = 4.63, P < 0.001, Cohen's d = 0.84); and learning interest stimulation (90.51 ± 2.27 vs. 84.63 ± 7.65, t = 4.12, P = 0.001, Cohen's d = 0.75).

Correlation analysis indicated that students' total assessment scores showed moderate to strong positive correlations with ratings in all four dimensions: clinical thinking (r = 0.84, P < 0.001); self-directed learning (r = 0.76, P < 0.001); teamwork ability (r = 0.72, P < 0.001); and learning interest stimulation (r = 0.79, P < 0.001). These correlations suggest consistency between teacher evaluations and objective assessment results (Table 5).

DISCUSSION

Summary of Main Findings: This randomized controlled trial provides evidence that a structured VR-based training system significantly enhances

Table 1: Comparison of General Information Between the Two Groups [x̄ ± s, n (%)]

Item	*Experimental Group (n=30)*	*Control Group (n=30)*	*t/χ² value*	*P value*
Age (years)	23.5 ± 0.48	23.5 ± 0.46	t = 0.09	0.93
Gender (Female)	15 (50%)	16 (53.3%)	χ² = 0.11	0.74
Prior Comp. GPA	82.4 ± 0.54	82.4 ± 0.56	t = 0.12	0.90

Table 2: Comparison of Assessment Results Between Groups (points, x̄ ± s)

Group	*Basic Theory (Total 30)*	*Surgical Theory (Total 30)*	*Surgery Operation (Total 40)*	*Total Score (Total 100)*
Experimental (n=30)	26.8 ± 2.1	27.3 ± 2.0	36.5 ± 2.5	90.6 ± 5.0
Control (n=30)	25.9 ± 2.3	26.5 ± 2.2	32.1 ± 3.0	84.5 ± 5.5
t value	1.58	1.45	6.12	4.50
P value	0.12	0.15	< 0.001	< 0.001

Table 3: Comparison of Subjective Evaluation Results Regarding Cardiovascular Surgery Clinical Practice Teaching Between Groups ($\bar{x} \pm s$)*

Evaluation Dimension	Experimental *Group (n=30)*	Control *Group (n=30)*	*t/Z value*	*P value*
1. Overall Experience of CV Surgery Practice (5-point)	4.45 ± 0.38	4.10 ± 0.75	2.28	0.027
2. Learning Effect & Confidence (5-point)	4.60 ± 0.32	3.05 ± 0.68	11.23	< 0.001
3. Immersion & Engagement (5-point)	4.72 ± 0.29	2.90 ± 0.82	11.87	< 0.001
4. Weekly Self-Directed Theory Learning Time (min)	88.5 ± 6.2	82.3 ± 7.5	3.48	0.001
5. Weekly Self-practice Surgical Skills Time (min)	66.8 ± 2.1	58.3 ± 4.5	9.37	< 0.001
6. VR Learning Interest Total Score (5-point)	4.73 ± 0.15	3.11 ± 0.66	12.89	< 0.001
6.1. Cognitive Interest Dimension	4.85 ± 0.18	3.20 ± 0.71	12.36	< 0.001
6.2. Affective Interest Dimension	4.80 ± 0.22	2.95 ± 0.73	12.67	< 0.001
6.3. Behavioral Interest Dimension	4.68 ± 0.25	2.88 ± 0.79	11.75	< 0.001
6.4. Persistent Interest Dimension	4.58 ± 0.29	2.80 ± 0.82	11.02	< 0.001

Note: Data for items 1, 2, 3, and 6 are derived from comprehensive scores of the 5-level VR-LIS questionnaire, where 5 is the full score.

Figure 1

a) PICO® VR system; b) Student using controllers to rotate, zoom, cut, and view through the virtual heart model within the VR system; c) VR intraoperative real-time teaching interface, showing the heart exposure pathway for total endoscopic cardiac surgery; d) Student using the VR system combined with a self-made simulator for endoscopic cardiac surgery simulation training.

Table 4: Student Questionnaire Survey Results Regarding the VR System [n (%)]

Questionnaire Item	*Strongly Agree*	*Agree*	*Neutral*	*Disagree*	*Strongly Disagree*
1 Image is realistic and natural	4 (13.3)	9 (30)	7 (23.3)	8 (26.7)	2 (6.7)
2 Good interactivity	8 (26.7)	12 (40)	6 (20)	4 (13.3)	0 (0)
3 Simple to control	9 (30)	15 (50)	3 (10)	3 (10)	0 (0)
4 VR device is comfortable to wear	12 (40)	13 (43.3)	2 (6.7)	3 (10)	0 (0)
5 Course content is rich	7 (23.3)	17 (56.7)	3 (10)	3 (10)	0 (0)
6 Teaching material recording is clear	10 (33.3)	14 (46.7)	6 (20)	0 (0)	0 (0)
7 Convenient for omnidirectional, multi-level viewing	15 (50)	15 (50)	0 (0)	0 (0)	0 (0)
8 Allows for detail zooming	9 (30)	19 (63.3)	1 (3.3)	1 (3.3)	0 (0)
9 No headache, dizziness, nausea, etc.	6 (20)	17 (56.7)	4 (13.3)	2 (6.7)	1 (3.3)
10 No eye dryness, pain, etc.	11 (36.7)	16 (53.3)	2 (6.7)	1 (3.3)	0 (0)
Total	91 (30.3)	147 (49.0)	34 (11.3)	25 (8.3)	3 (1.0)

Table 5: Comparison of Student Learning Ability and Interest Evaluation (points, $\bar{x} \pm s$) and Correlation Analysis with Total Assessment Score

Indicator	*Experimental Group (n=30)*	*Control Group (n=30)*	*t value*	*P value*	*Cohen's d*	*Correlation with Total Score (r)*	*P value for Correlation*
Clinical Thinking	91.23 ± 3.64	80.45 ± 5.56	8.98	< 0.001	1.63	0.84	< 0.001
Self-Directed Learning	89.45 ± 4.48	82.76 ± 8.31	4.02	0.001	0.73	0.76	< 0.001
Teamwork Ability	88.62 ± 3.35	83.63 ± 4.82	4.63	< 0.001	0.84	0.72	< 0.001
Learning Interest Stimulation	90.51 ± 2.27	84.63 ± 7.65	4.12	0.001	0.75	0.79	< 0.001
Total Score (100)	90.60 ± 5.0	84.50 ± 5.5	4.5	< 0.001	0.82	---	---

the surgical skill acquisition, overall clinical performance, and learning engagement of students compared to conventional apprenticeship-based methods. The experimental group achieved significantly higher scores in hands-on surgical simulation and total clinical assessment, while also demonstrating substantially greater learning interest, immersion, and self-directed practice time.

Interpretation of Findings: The superior performance in hands-on surgical simulation aligns with the core advantage of ViR technology: providing safe, repetitive, and structured practice in a high-fidelity environment.[4,5,7,9] This is particularly crucial in cardiac surgery, where early real-patient practice is limited by operative risk and resource constraints. The immersive three-dimensional models likely enhanced spatial understanding of complex cardiac anatomy, consistent with previous findings in neurosurgical and urological training.[7,8,13] The interactive decision points within simulations may have fostered improved clinical reasoning, as reflected in higher teacher ratings for clinical thinking ability.

The significant increase in self-directed practice time and learning interest suggests that VR can motivate students and promote active learning, addressing a key limitation of passive observation in traditional models.[14,15] The 52.1% increase in overall learning interest scores and the 62.8% improvement in immersion and engagement indicate that these technologies may transform the learning experience from obligatory participation to intrinsic motivation.

Mechanisms of Educational Efficacy: Several mechanisms may explain the observed benefits. First, VR technology transforms two-dimensional imaging into interactive three-dimensional cardiac models, enabling operations such as rotation, zooming, and layered viewing. This functionality substitutes for cadaveric anatomical specimens to some extent and significantly enhances spatial cognition of complex structures.[7,8,13-15] Second, virtual surgery simulation enables repeated practice in a risk-free environment, facilitating deep integration of theory and practice through familiarization with approach selection, instrument use, and suturing techniques.[7-10] Third, the system supports scenario-based learning by simulating diverse disease presentations and surgical situations, systematically cultivating clinical thinking and judgment.[8,13]

Furthermore, VR technology supports remote collaboration and multi-user interaction, potentially overcoming limitations of uneven instructor distribution and resource availability.[17-19] Although this study did not specifically examine remote teaching, the constructed platform possesses potential for future development of 5-G wireless-based remote training systems.

Cost-Effectiveness and Scalability of the System: A notable strength of the system developed in this study lies in its construction from commercially available, off-the-shelf VR hardware and accessible software tools. The platform utilized the PICO Ultra 4 head-mounted display system, a consumer-grade device, combined with standard 4K panoramic cameras and the Unity3D engine for video integration. Through straightforward video processing and script programming, we created a functional and effective training system without requiring proprietary or highly specialized equipment. This approach resulted in relatively low initial development costs and provides a foundation for subsequent upgrades and expansions as technology advances.[11]

This cost-effective and flexible architecture carries significant implications for broader implementation. As VR technologies continue to mature and become more affordable, individual medical centers can adapt this framework to develop customized training systems tailored to their specific institutional needs. Centers may design modules reflecting their predominant patient populations, primary disease profiles, and characteristic surgical approaches. For example, a center specializing in valvular heart disease may emphasize mitral and aortic valve procedures, while another focusing on congenital heart surgery may prioritize septal defect repairs and complex reconstructions. Similarly, institutions with varying resource levels can scale the system complexity accordingly, from basic anatomical visualization to advanced haptic-integrated simulation.

This adaptability is particularly relevant for healthcare systems in developing regions or institutions with limited educational budgets, where expensive commercial simulation platforms may be inaccessible. By demonstrating that effective VR surgical training can be built using widely available components and open-source or low-cost software, this study provides a practical roadmap for democratizing access to high-quality surgical education. Future multi-center collaborations could further validate this modular approach and establish best practices for local customization, ultimately contributing to more equitable distribution of advanced surgical training resources globally.

Limitations: This study has several limitations. First, the single-center design with a relatively limited sample size (n=60) may restrict generalizability. Multi-center, large-sample randomized controlled trials are needed to validate these findings across diverse institutional settings. Second, technical parameters of the VR system require optimization. Student-reported adverse reactions including dizziness (20.0% non-positive) and eye discomfort (13.3% non-positive) indicate needs for hardware improvement, including higher refresh rates, reduced headset weight, improved interpupillary distance adjustment, and implementation of rest protocols. Third, existing systems primarily focus on three-dimensional anatomical modeling. Integration with force feedback devices and superposition of real medical images remain immature, limiting the ability to fully simulate tactile sensation and team coordination of real surgeries.[1,5] Fourth, constrained by the clinical training schedule, this study did not conduct long-term follow-up assessments of knowledge and skill retention. Future research should extend follow-up periods to investigate the sustained impact of VR teaching on clinical competencies and real surgical performance. Fifth, although both groups received standardized orientation to the VR assessment interface prior to evaluation and the assessment tasks avoided complex fine manipulations, the control group lacked equivalent VR-based practice experience during the intervention period. This may have introduced a familiarity bias favoring the experimental group. Future studies should incorporate additional assessment modalities—such as cadaveric or porcine models, or objective structured assessment of technical skills (OSATS) in simulated wet-lab settings—to complement VR-based evaluation and reduce modality-specific bias.

Conclusions: This study provides encouraging evidence that a VR-based training system can significantly enhance medical students' learning interest, clinical abilities, and assessment scores during their cardiac surgery rotation compared to traditional teaching methods. However, the single-center design, modest sample size, lack of long-term follow-up, and potential assessment modality bias warrant caution in generalizing these findings. The positive results support VR as a promising pedagogical adjunct in cardiac surgery education, but further multi-center, large-sample randomized controlled trials with extended follow-up and diverse assessment modalities are needed to confirm its effectiveness and generalizability. As VR technology continues to evolve, it holds potential to contribute meaningfully to surgical education, provided that rigorous evidence continues to accumulate.

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