DOI: https://doi.org/10.17816/DD635577

Potential use of virtual and augmented reality technologies in modern cardiology and cardiac surgery

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ABSTRACT

Innovative technologies have dramatically changed medical practice, particularly in cardiac surgery, which requires precision and caution due to the challenging nature of procedures. The use of virtual reality (VR) and augmented reality (AR) in this area has great potential to improve surgical planning, medical education and patient outcomes.

This review analyzes the literature on the role of VR and AR in modern cardiology and discusses possible directions for their development.

The search retrieved 3,858 publications from PubMed/MEDLINE, 69 publications from eLibrary, and 1,115 publications from Google Scholar. Searches included the following keywords and combinations thereof: virtual reality; augmented reality; cardiology; cardiac surgery. Publications were searched from the time the relevant databases were created to May 2024.

Cardiac care today involves increasingly sophisticated procedures that require a high level of expertise. VR becomes a powerful tool for both surgical planning and education. It opens new opportunities for educating and training cardiologists. It can be used to create realistic simulations of situations healthcare professionals may encounter in their practice. Students are able to gain hands-on experience with no risk to real patients. Integrating virtual reality into cardiology practice has great potential, but several issues need to be addressed. Standards for safety and efficacy of the medical use of virtual reality should be developed. Further research is also needed to assess the long-term health effects of VR use on patients.

Keywords: artificial intelligence; virtual reality; augmented reality; cardiology; imaging; training.

To cite this article:

Rashidova SS, Bdoyan EA, Timurzieva MM, Lobanovskaya SA, Naumenko VV, Rakhmanova AV, Timofeeva VD, Gutsulyak AS, Zainullin AA, Uzbekova KR, Kharitonova VA, Akhmetova NF. Potential use of virtual and augmented reality technologies in modern cardiology and cardiac surgery. *Digital Diagnostics.* 2024;5(4):819–832. DOI: https://doi.org/10.17816/DD635577

Received: 01.09.2024 **Accepted:** 25.09.2024 **Published online:** 05.11.2024

DOI: https://doi.org/10.17816/DD635577

Возможности применения технологий виртуальной и дополненной реальности в современной кардиологии и кардиохирургии

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АННОТАЦИЯ

Технологические инновации произвели революцию в медицинской практике, особенно в области кардиохирургии, где сложный характер вмешательств требует точности и предусмотрительности. Использование виртуальной и дополненной реальности в этой области открывает огромные перспективы для улучшения предоперационного планирования, повышения качества медицинского образования и, в конечном счёте, улучшения результатов лечения пациентов.

В данном обзоре проанализирована литература, посвящённая роли виртуальной и дополненной реальности в современной кардиологии, а также обсуждаются возможные направления развития данной области.

В результате поиска извлечено 3858 публикаций из PubMed/MEDLINE, 69 публикаций из eLibrary и 1115 публикаций, найденных с помощью Google Scholar. Поисковые запросы включали следующие ключевые слова и их сочетания: виртуальная реальность; дополненная реальность; кардиология; кардиохирургия; virtual reality; augmented reality; cardiology; cardiac surgery. Временной интервал поиска: с момента основания соответствующих баз данных по май 2024 года.

Современная кардиологическая помощь включает в себя всё более сложные процедуры, требующие высокого уровня квалификации. Виртуальная реальность становится мощным инструментом как для предпроцедурного планирования, так и для образовательных мероприятий. Она открывает новые возможности для обучения и подготовки специалистов в области кардиологии. С её помощью можно создавать реалистичные симуляции различных ситуаций, с которыми врачи могут столкнуться в своей работе. Это позволяет обучающимся получить практический опыт без риска для реальных пациентов. Интеграция виртуальной реальности в кардиологическую практику имеет большой потенциал, однако для этого необходимо решить ряд проблем. Следует разработать стандарты безопасности и эффективности использования виртуальной реальности в медицинских целях. Также необходимо провести дополнительные исследования, чтобы оценить долгосрочные последствия её использования для здоровья пациентов.

Ключевые слова: искусственный интеллект; виртуальная реальность; дополненная реальность; кардиология; визуализация; обучение.

Как цитировать:
Рашидова С.С., Бдоян Э.А., Тимурзиева М.М., Лобановская С.А., Науменко В.В., Рахманова А.В., Тимофеева В.Д., Гуцуляк А.С., Зайнуллин А.А., Узбекова К.Р., Харитонова В.А., Ахметова Н.Ф. Возможности применения технологий виртуальной и дополненной реальности в современной кардиологии и кардиохирургии // Digital Diagnostics. 2024. Т. 5, № 4. С. 819–832. DOI: https://doi.org/10.17816/DD635577

Рукопись получена: 01.09.2024 **Рукопись одобрена:** 25.09.2024 **Опубликована online:** 05.11.2024

ЭКО • ВЕКТОР

DOI: https://doi.org/10.17816/DD635577

在现代心脏病学和心脏外科中应用虚拟现实和增强现实技术的可能性

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摘要

技术创新彻底改变了医疗实践，特别是在心脏外科领域，干预的复杂性需要精确性和预见性。虚拟现实和增强现实在该领域的应用，对于改善术前规划、提高医学教育质量，并最终改善患者治疗效果，具有巨大的前景。

本综述分析了虚拟现实和增强现实在现代心脏病学中的作用的文献，并讨论了该领域可能的发展方向。

最终从PubMed/MEDLINE检索到3858篇发表文章，从 eLibrary检索到69篇发表文章，并使用Google Scholar检索到1115篇发表文章。搜索查询包括以下关键词及其词组：虚拟现实；增强现实；心脏病学；心脏外科；virtual reality；augmented reality；cardiology；cardiac surgery。检索时间间隔：自各数据库建库至2024年5月。

现代心脏护理，包括日益复杂的程序，需要高水平的专业知识。虚拟现实正在成为程序前规划和教育活动的强大工具。它为心脏病学的教育和培训提供了新的可能性。它可对医生在工作中可能遇到的各种情况进行真实的模拟。这使得学员能够获得实践经验，而真正的患者无需承担风险。将虚拟现实融入心脏病学实践具有巨大潜力，但为此必须解决许多问题。应制定将虚拟现实技术用于医疗目的的虚拟现实的安全性和有效性的标准。还需要进一步的研究来评估其使用对患者健康的长期影响。

关键词：人工智能；虚拟现实；增强现实；心脏病学；可视化；学习。

引用本文：
Rashidova SS, Bdoyan EA, Timurzieva MM, Lobanovskaya SA, Naumenko VV, Rakhmanova AV, Timofeeva VD, Gutsulyak AS, Zainullin AA, Uzbekova KR, Kharitonova VA, Akhmetova NF. 在现代心脏病学和心脏外科中应用虚拟现实和增强现实技术的可能性. *Digital Diagnostics*. 2024;5(4):819–832. DOI: https://doi.org/10.17816/DD635577

收到：01.09.2024 **接受：**25.09.2024 **发布日期：**05.11.2024

INTRODUCTION

Modern healthcare is seeing a global trend toward the utilization of virtual, augmented, and mixed reality [1]. *Virtual reality* (VR) systems use computerized three-dimensional digital information visualization to simulate real or virtual objects. VR technology was invented in the 1950s [2]. It had undergone substantial change by the 1980s and was the subject of in-depth preclinical research [3]. Notably, the introduction of head-mounted displays with a frontal screen (also known as VR headsets) in the 1980s marked a shift in medical imaging [4]. During the process, VR headset components continuously travel back and forth to create 3D images [5].

Augmented reality (AR) is characterized by the seamless integration of virtual elements and reality. Unlike VR, which fully immerses the user in a simulated digital reality, AR incorporates virtual information into the user environment. AR functions are implemented via gadgets like smartphones, tablets, and head-mounted devices outfitted with transparent glasses or projectors that project virtual images directly into the real world [6–8]. This difference serves as the foundation for investigating the unique properties of both virtual and augmented reality in the context of the advancement of cardiac surgery.

Innovative technologies have significantly altered medical practice, particularly cardiac surgery, which requires precision and caution due to the challenging nature of the procedures. The application of VR and AR in this field has great potential for improving surgical planning, medical education, and patient outcomes.

DATA SEARCH METHODOLOGY

Publications were assessed in accordance with the *PRISMA* guidelines. The selection algorithm is presented in Fig. 1.

The search yielded 3,858 publications from *PubMed/MEDLINE*, 69 publications from *eLIBRARY.RU*, and 1,115 publications from *Google Scholar* databases. The search terms included the following keywords and their combinations: *виртуальная реальность (virtual reality), дополненная реальность (augmented reality), кардиология (cardiology),* and *кардиохирургия (cardiac surgery)*. Publications from the creation of pertinent databases to May 2024 were searched. All authors independently screened the titles and abstracts of the identified publications. When relevant studies were found, the full text of the respective publications was retrieved. Duplicates and non-full-text publications were excluded. Full-text publications were assessed for compliance with the following inclusion criteria:

- Publications in either English or Russian;
- Publications in peer-reviewed journals;
- Reviews, experimental studies, and clinical studies containing the specified keywords.

After screening, 55 publications were included in the review.

ROLE OF VIRTUAL REALITY IN INTERVENTIONAL CARDIOLOGY

Peri-procedural VR and AR technologies are modern technologies that generate 3D images of anatomical structures for facilitating pre- and postoperative planning. VR enables radiologists to examine complex anatomy in a virtual world [9, 10], whereas AR assists in applying digital data to patients both before and after surgery. Rymuza et al. described the preoperative use of *CarnaLife Holo* in a patient with bicuspid aortic valve stenosis [11]. Radiologists could visualize a 3D hologram of the heart during a successful *transcatheter aortic valve replacement* (TAVR). Both VR and AR technologies enable the modeling of congenital

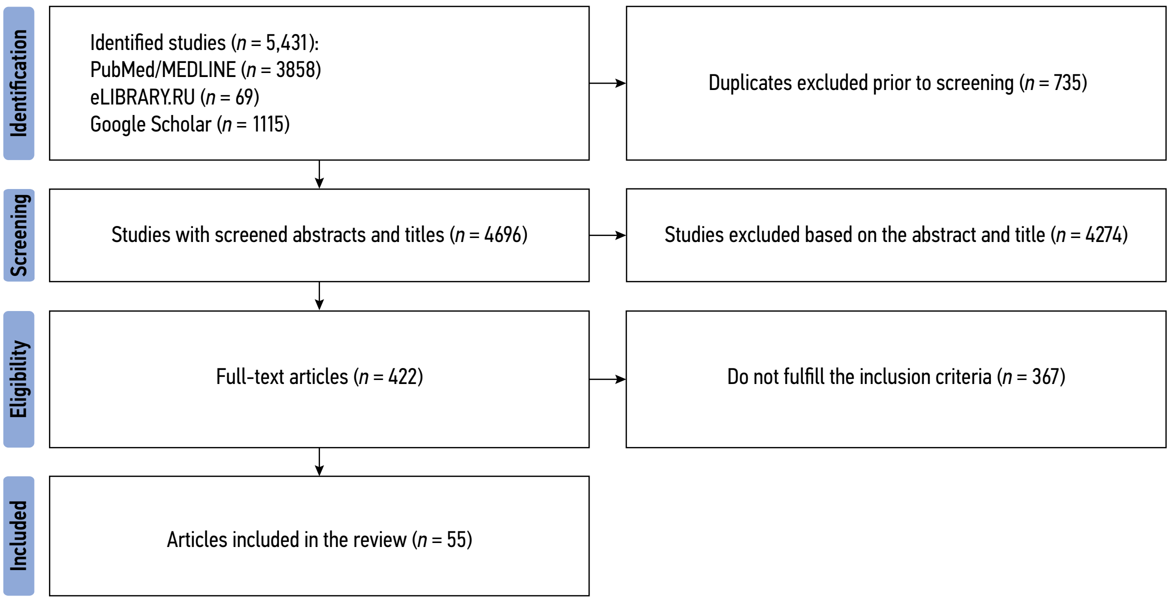

Fig. 1. Publication search algorithm.

DOI: https://doi.org/10.17816/DD635577

heart diseases as well as various phases of structural heart interventions such as TAVR and other valvular interventions [12–14]. Endovascular occlusion of the *left atrial appendage* (LAA), electrophysiological ablation, and TAVR are complex interventions that require a thorough understanding of the cardiac anatomy [15]. TAVR can be modeled by developing individual models and identifying the optimal site for prosthetic aortic valve placement. Several factors can be considered when determining this site, including valve morphology and calcification, presumed distances to relevant structures in cardiac conduction disorders, and coronary ostia, which are useful in other interventions such as LAA occlusion or transaortic reconstruction of the posterior mitral leaflet. In these cases, mitral valve interventions can be planned after determining the precise transseptal puncture site [16]. VR simulators assist in selecting the optimal surgical approach, thereby mitigating the risk of fatal complications such as aortic perforation, mitral valve apparatus destruction, left ventricular outflow tract obstruction, or coronary artery damage. Additionally, radiologists employ real-time X-ray imaging to assess the patient's anatomy. Furthermore, they can use alternative imaging modalities such as preoperative *computed tomography* (CT), cardiac *magnetic resonance imaging* (MRI), and *echocardiography* (ECG). These techniques can also be useful for pericardiocentesis and electrophysiological procedures [17].

In addition to the benefits of VR for physicians, it can also be used to improve patient comfort during treatment. For example, immersive VR promotes positive emotions and improves mood by synchronizing and stabilizing electric pulses in the prefrontal cortex, thereby reducing pain and discomfort [18]. Several studies have assessed the impact of VR on interventional cardiology procedures using different applications and multimedia content.

Based on the *State-Trait Anxiety Inventory* score, Keshvari et al. demonstrated that undergoing a 5-min VR session featuring natural scenarios and sounds, such as quiet music and sounds of birds and waterfalls, prior to *coronary angiography* (CAG) reduced anxiety levels [19]. There were significant differences in outcomes between the treatment group and the control group participants who received the conventional treatment. Moreover, the authors found that a 5-min VR session stabilized the heart rate and blood pressure [19].

Aardoom et al. reported that the VR-based training content administered one or two weeks before undergoing CAG reduced the procedure-related anxiety. Patients used a VR headset at home or in a clinic to virtually review all surgical stages, from admission to the postoperative period. The training addressed diverse medical care-related topics, including behavior in a hospital ward, clothing for patients, persons who can accompany them, and drugs prescribed after surgery. Patients could interact with healthcare personnel avatars to obtain essential information about each stage. The VR session lasted approximately 20 minutes; however, the time spent in each module likely affected how long it lasted [20].

Morgan et al. found a considerably greater decline in anxiety in patients who received a 10-min VR training session prior to CAG, which explained the pre-procedure phase and the procedure, compared with the control group. Moreover, compared to the control group, the treatment group understood the procedure better and expressed greater satisfaction with the outcomes. In a clinical study by Gökçe and Arslan, VR-based training for patients undergoing CAG was more effective in lowering pain and anxiety, as well as improving patient comfort, systolic blood pressure, respiratory rate, and heart rate, compared to conventional treatment in the control group [22].

VR has also been employed in patients who received conscious sedation[1] during TAVR. Patients in the treatment group received a 30-min VR session in a relaxing environment of their choice. Overall, 91.3% of the patients used VR prior to undergoing the procedure, while 37.5% used it during the procedure. A significant decrease in anxiety was noted on the *visual analog scale* (VAS) [23] compared to the control group participants who received conventional TAVR. However, these findings should be interpreted with caution due to the small sample size (32 patients) [23].

VR can be used prior to administering catheter-based ablation for *atrial fibrillation* (AF). The procedure boosted patient awareness, self-efficacy, and satisfaction while mitigating the anxiety associated with surgery [24–26]. Moreover, the use of VR prior to ablation effectively reduced anxiety and pain during the surgery [26]. Brewer et al. used VR in 40 patients who underwent unilateral radiofrequency ablation of the great saphenous vein. All procedures were successful, with no variations in the overall surgery time, and every patient was largely satisfied with the treatment. VR significantly reduced surgery-related anxiety compared to the control group that received standard care. Moreover, during surgery, anxiety increased in the control group but decreased in the VR group. Finally, 85% of the VR group participants indicated that they would recommend VR to others undergoing this surgery [27].

ROLE OF VIRTUAL REALITY IN HEART FAILURE TREATMENT

In addition to its use in interventional procedures, VR can assist with the anatomical planning of *mechanical circulatory support*. In the treatment of *heart failure* (HF), it is essential to understand the interactions between hemodynamics and the anatomy and function of the myocardium and valves. One example is the use of *ventricular assist devices* (VADs)

[1] Conscious intravenous sedation is a technique that uses sedative drugs to induce light sleep.

in patients with different ventricular shapes, sizes, and functional characteristics. Modern VADs can be used in children as a foundation for therapy prescription. VAD implantation using VR simulation can assist in determining both the design and the best position of the device in a specific patient, considering anatomical features [28]. Specifically, virtual models enable the real-time testing of VAD implantation and the determination of the appropriate orientation of the cannula. The proper position of the cannula (parallel to the *septum*, in line with the atrioventricular valve) is crucial for achieving optimal outcomes. Improper positioning can impede blood flow, resulting in thrombosis. Preoperative assessment can be useful for preventing complications, especially in children, who can develop complications associated with left ventricular failure following surgery. Patient-specific models can also provide critical insights on the spatial relationship between a VAD and major structures such as the interventricular septum and coronary arteries, the orientation of cardiac valves, and the interactions between extracardiac devices and the chest wall and diaphragm.

Stepanenko et al. described their experience with 3D printing and VR in 53 adult patients with progressive HF [29]. 3D modeling facilitated optimal clinical decisions on the type of mechanical circulatory support to be administered. Similarly, Davies et al. [30] and Ramaswamy et al. [31] described the use of VR to assess the placement of the *HeartWare VAD* (HVAD; Medtronic, Dublin, Ireland) and *HeartMate 3* (Abbott, Chicago, Illinois) intrapericardial devices in children.

Furthermore, these models can be used for surgeon training because they enable physical manipulation and implant testing, boosting surgeons' confidence during interventions. Thus, VR reconstructions and specialized 3D models can facilitate precise surgical planning, identify potential risks, and assist in patient-specific medical emergency planning.

ROLE OF VIRTUAL REALITY IN PREPROCEDURAL PLANNING

The advancement of digital technology continuously modifies knowledge and opportunities in cardiac care [32]. It is now possible to use *artificial intelligence* (AI) for performing automated ECGs and robot-assisted surgery in minimally invasive mitral valve procedures. Complex structural cardiovascular interventions require adequate technical competence and preparedness for any unexpected life-threatening complications. Progress in this area is based on advancements in multimodal visualization, optimizing measurements, calibration, and preprocedural planning. VR technologies can play a significant role in this field as a useful tool for both patients and physicians.

Interactive 3D images and VR simulators can facilitate the imaging of complex heart anatomy for determining the best treatment strategy (percutaneous or surgical intervention).

In cases where neighboring structures or severe calcification can prevent the use of modern imaging tools, VR in combination with other imaging techniques, such as ECG and cardiac CT, allows for precise surgical planning and the determination of appropriate implantation sites for TAVR or MitraClip-based techniques [15, 16]. Similar to flight simulators, modern VR systems can ensure patient safety by predicting and preventing fatal complications, such as implant displacement, aortic perforation, and acute coronary syndrome [16].

INTRA-PROCEDURAL APPLICATION OF VIRTUAL REALITY

VR is used in many complex cases, such as mitral valve interventions with varied and complex mitral valve anatomy, which typically require multimodal visualization for optimal outcomes [26]. VR augments accuracy and lowers the procedure time compared to conventional transesophageal ECG. Moreover, VR can enhance paravalvular regurgitation imaging following TAVR and assist in VAD selection [33, 34].

In congenital heart diseases, such as *atrial septal defects* with abnormal pulmonary venous drainage, VR prevented errors in transseptal puncture in combination with CT and biplanar X-ray imaging [33, 35, 36]. Furthermore, VR can facilitate the comprehensive assessment of the LAA and adjacent structures, such as the pulmonary artery and circumflex artery, in LAA occlusion associated with AF and high-risk bleeding [33]. A holographic model of the heart can be made utilizing a holographic environment made with 3D pictures from an ECG or CT scan, allowing for interactive device control using voice commands and movements. This makes the platform convenient for performing cardiac surgery [37].

ROLE OF VIRTUAL REALITY IN CONGENITAL HEART DISEASE

Procedure planning in *congenital heart diseases* (CHDs) can be challenging due to their wide spectrum and diverse clinical manifestations. In cardiology, VR is utilized for training and procedure planning. Its use began during the preclinical stage of implantable device development. Moreover, it has been used for creating and testing prototypes prior to animal studies and subsequent strictly regulated tests for implanting these devices in humans.

Because of their ease of cropping, surface mesh models based on the manual segmentation of CT, angiography, or cardiac MRI scans assist cardiac surgeons in surgical planning [38]. However, their development can be challenging. Raimondi et al. described the use of a novel VR technology for cardiac MRI data processing without intermediate segmentation stages. The average post-processing duration for the VR models using this software was five minutes [39].

Full-immersion VR significantly improved the diagnostic accuracy in heart diseases compared to a 2D display and VR software (by 54.49% and 146.82%, respectively). There were no significant differences between the diagnostic data provided to each study participant ($t = -1.01$, $p = 0.31$) [40]. Another study compared the efficacy of stereoscopic VR and a monoscopic PC. The evaluation of the anatomy in CHDs was not enhanced by stereoscopic VR ($p = 0.11$). The group of patients receiving monoscopic PC reported that its interface was more user-friendly than that of the stereoscopic VR ($p = 0.01$) [41].

Recent studies comparing VR and 3D-printed heart models in CHDs revealed that VR was more useful in medical training and preoperative planning than 3D-printed models; however, the differences were not statistically significant [42]. Similar findings were noted during a VR session while assessing anatomical features in patients with CHDs. Healthcare professionals with diverse expertise and experience (cardiac surgeons, cardiologists, cardiac anesthesiologists, pediatricians, and pathologists) and medical students participated in the session. In total, 72% of the participants rated the VR interaction methods (e.g., grasping objects, using cutting tools) as "extremely intuitive," and 94% were willing to implement the VR system in their institutions, awarding it four or five points on a 5-point scale [43].

A medical facility must make significant investments in the necessary infrastructure, software, screens, and VR headsets before implementing VR. However, compared to 3D printing, the cost of the equipment and materials for 3D printing, as well as the operating expenses, remain constant. VR enables the editing and updating of visualized 3D models and meshes as necessary, saving them in a digital format, and linking them to medical records for future use [44].

VR is particularly beneficial in planning complex intra- and extracardiac interventions. For example, a research group of pediatric cardiac surgeons reported increased confidence when planning and performing surgeries in two-thirds of cases and improvements in the surgical strategy in 60% of cases [38]. Davies et al. reported the use of VR to plan adult VAD placement in a child (17 kg, 0.67 m^2). This approach preserved the atrioventricular valve function and reduced the distortion of the cardiac structures [30]. The use of VR is currently limited to a few centers; however, it is gaining acceptance in academic and therapeutic organizations.

VIRTUAL REALITY EXPANSION USING ARTIFICIAL INTELLIGENCE

AI is essential for complicated and multidomain data processing in VR and AR, facilitating the adoption of novel technologies. More specifically, AI contributes to VR functionality in three areas:

Segmentation: AI facilitates accurate and rapid data labeling. Deep learning algorithms enable structure tracking, which can be totally automated or supervised. The pre-processing time is reduced from several days to several minutes, making this step crucial for implementing VR in clinical practice [38, 45].

Reconstruction: AI enables human model reconstructions in VR for specific applications, such as coronary artery modeling with automatic calculation of atherosclerotic plaque volume or echocardiogram conversion into a VR model with 3D anatomy and blood flow visualization for surgical planning [38]. This step allows the user to focus on the work in the virtual environment rather than the application settings [46]. Franson et al. developed a system that converts 2D MRI images into interactive 4D structures that users can view in real time, with the rendering speed exceeding the data collection speed [47]. Similarly, the solution proposed by Bindschadler et al. was further refined, making it possible to manipulate cardiac models in AR. These models can be viewed on mobile devices using simple gestures, a function optimized for patient counseling [48].

Man–machine interaction: User interactions with VR can generate vast volumes of multidomain data, which must be integrated with reduced dimensions, upgraded machine learning, and user–VR interactions. This function is primarily employed in medical training [49, 50]. Moreover, this technology can mitigate VR sickness, which many users find to be a limitation. This is achieved by using a system with six degrees of freedom, which boosts oculomotor responses and reduces the spatial disorientation that induces nausea and dizziness [51].

These features allowed systems like *Immersive* and *Elucis* to create VR platforms. These platforms can be used for a single examination with cardiac imaging, procedure planning, remote communication between experts, and patient counseling. Moreover, they allow preservation of models for training, thus enabling delivery of high-quality medical care.

PROSPECTS

The use of VR can immensely impact modern cardiology. Integration of CT, MRI, and ECG findings is still a developing area, with the possibility of real-time data fusion and generating high-resolution 3D anatomical structures [52, 53]. Modern cardiac surgery procedures are becoming increasingly complex and demand excellent skills [53, 54]. VR can be used as a training tool for acquiring the skills required for clinical practice. Moreover, VR eliminates geographic barriers, providing easy access to training programs and conferences and offering practical experience. Patients can also benefit from these educational opportunities, enhancing their comprehension of human anatomy and surgical procedures. VR-based technologies are ready to be incorporated into standard treatment plans and be implemented in medical institutions [53, 55].

However, several issues must be addressed before VR is extensively used in clinical practice. Most published studies are small-scale, including a small number of cases, and are performed in individual centers. Reliable VR efficacy assessment in clinical practice requires large-scale studies and randomized clinical trials. Moreover, the methods must be standardized to ensure consistency and facilitate widespread use. The integration of multimodal images is ongoing, although it has not yet reached its full potential. Furthermore, the use of diverse VR platforms, each requiring developing special skills, can present users with additional challenges. The introduction of VR in clinical practice can add to the existing heavy workload. Despite the promising future of VR in medicine, it is extremely important to conduct randomized clinical trials to validate its utility.

Although difficulties exist, the value of VR in clinical practice has become increasingly obvious. VR use in healthcare requires ongoing technological advancements and standardized applications to reach its full potential.

CONCLUSION

cardiac care today entails performing increasingly sophisticated procedures that require a high level of expertise. In this context, VR becomes a powerful tool for both preprocedural planning and training. It opens new opportunities for training cardiologists. It can be used to create realistic simulations of various situations that healthcare professionals may encounter in their practice. Students can obtain practical experience without endangering actual patients. Moreover, VR can be used for preprocedural planning of complex cardiac surgeries. It allows for the comprehensive assessment of patient anatomy, surgical planning, and predicting potential complications. This can significantly improve surgical accuracy and safety. However, several issues must be addressed before VR becomes widely used in clinical practice. It is necessary to create guidelines for the effectiveness and safety of VR in medical contexts. Moreover, further research is needed to determine the long-term health effects of VR use. Overall, VR integration in cardiology exhibits great potential. It can significantly improve medical care quality, reduce risks, and facilitate training. To fully maximize this potential, additional research and relevant standards are required.

ADDITIONAL INFORMATION

Funding source. This article was not supported by any external sources of funding.

Competing interests. The authors declare that they have no competing interests.

Authors' contribution. All authors made a substantial contribution to the conception of the work, acquisition, analysis, interpretation of data for the work, drafting and revising the work, final approval of the version to be published and agree to be accountable for all aspects of the work. S.S. Rashidova, E.A. Bdoyan — collection and analysis of literary data, scientific editing of the manuscript; M.M. Timurzieva, S.A. Lobanovskaya — collection and analysis of literary data, writing of the manuscript; V.V. Naumenko — analysis of literary data, editing of the text of the manuscript; A.V. Rakhmanova — data analysis, editing and approval of the text; V.D. Timofeeva — writing a manuscript, extraction and analysis of literary data; A.S. Gutsulyak — editing the text of the article, analyzing literary data; A.A. Zainullin — collecting literary data, writing the text of the article; K.R. Uzbekova — approval of the final version of the manuscript, editing the text of the article; V.A. Kharitonova — analysis of literary data, assistance in writing the article; N.F. Akhmetova — analysis of literary data, assistance in writing the article, verification and approval of the text of the article.

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