Dariusz Mikolajewski, Anna Bryniarska
Piotr Michal Wilczek, Maria Myslicka
Adam Sudol, Dominik Tenczynski
Michal Kostro, Dominika Rekawek
Rafal Tichy, Rafal Gasz
Mariusz Pelc, Jaroslaw Zygarlicki
Michal Koziol, Radek Martinek
Radana Kahankova Vilimkova, Dominik Vilimek
Aleksandra Kawala-Sterniuk

THE MOST CURRENT SOLUTIONS USING VIRTUAL-REALITY-BASED METHODS IN CARDIAC SURGERY – A SURVEY

Abstract *There is a widespread belief that VR technologies can provide controlled, multisensory, interactive 3D stimulus environments that engage patients in interventions and measure, record and motivate required human performance. In order to investigate state-of-the-art and associated occupations we provided a careful review of 6 leading medical and technical bibliometric databases. Despite the apparent popularity of the topic of VR use in cardiac surgery, only 47 articles published between 2002 and 2022 met the inclusion criteria. Based on them, VR-based solutions in cardiac surgery are useful both, for medical specialists and for the patients themselves. The new lifestyle required from cardiac surgery patients is easier to implement thanks to VR-based educational and motivational tools. However, it is necessary to develop the above-mentioned tools and compare their effectiveness with Augmented Reality (AR). For the aforementioned reasons, interdisciplinary collaboration between scientists, clinicians and engineers is necessary.*

Keywords virtual reality, cardiac surgery, clinical applications, surgical training, image processing

Citation Computer Science 25(1) 2024: 107–128

1. Introduction

The enthusiasm of the use of virtual reality (VR) in cardiac surgery is relatively short, although, the first scientific publications on the subject appeared in 2002 [40,75]. However, the growing interest and importance of the combination of the above mentioned technologies for the future of interventional cardiac surgery and the imaging of cardiovascular function in the form of virtual twins puts the subject at the centre of interest for engineers and clinicians alike [82]. In addition to preventive medicine or bespoke cardiac interventions, this includes regenerative surgery in the form of the emerging possibility of 3D printing tissues from bio-ink (in most cases: the patient's stem cells) through reverse engineering (3D scan – modification – 3D printing) [26, 93]. We are already able to print other human tissues, such as skin (innervated and vascularised), but larger and more complex organs such as the pancreas, liver, lungs or just the heart have so far been beyond our reach. The development of VR in cardiac surgery could be a good step in this direction, heralding new possibilities, including those based on the Internet of Things, integrating them into the Healthcare 4.0 paradigm and expanding the capabilities of the cardiac surgeon [45, 99].

The main aim of this paper is to summarise the current and emerging future opportunities for VR-based support of cardiac surgery, also with reference to the observed Virtual-Augmented Reality (VR-AR) rivalry in both, industrial (Industry 4.0) and clinical applications [70, 88].

The most recent technological advances inevitably bring medical improvements, giving professionals increasingly effective diagnostic, therapeutic, rehabilitation and care tools, including automated and semi-automated long-term care [25, 54, 79]. Placing this article in a broader context, we can see immediately that this is highly interdisciplinary research, combining technical sciences (computer science, mechatronics, material engineering) with medical and health sciences (including not only cardiology, but also medical imaging, biotechnology, and tissue engineering), as well as the humanities and social sciences (including psychology) [21, 33]. The relevance of the above-mentioned research goes beyond its scientific and clinical context, being of great economic and social importance, both towards increasing health-related quality of life (HRQoL) and making it easier for people with cardiovascular conditions to learn, work and play, as well as ageing more cheerfully [56, 78, 101].

In this paper, we propose not only an overview of the current state of the art, but will carefully consider a number of hypotheses for the further development of this area of knowledge and practice, including a better understanding of the physiological and pathological mechanisms of the cardiovascular system, advances in didactics on virtual cardiac simulations, the role of medical simulation in the training of cardiac surgeons, the preparation of cardiac procedures (e.g. analysis of access routes) in the case of a specific patient, not shying away from the cardiac surgery of the future: virtual patient twins and prediction of the progress of natural tissue wear and tear or risk of injury [3, 24, 37]. It seems that this holistic approach to the topic under discussion will be of benefit to both engineers and clinicians, allowing them to delve deeper into the subject and develop their own replication of the cited studies or further research.

2. Materials and Methods

We provided a careful review of 6 leading medical and technical bibliometric databases (PubMed, EBSCO, EMBASE, PEDro, dblp, and ACM Digital Library) using specified keywords (virtual reality, VR, cardiac surgery, and similar) in accordance with the review methodology shown in Figure 1.

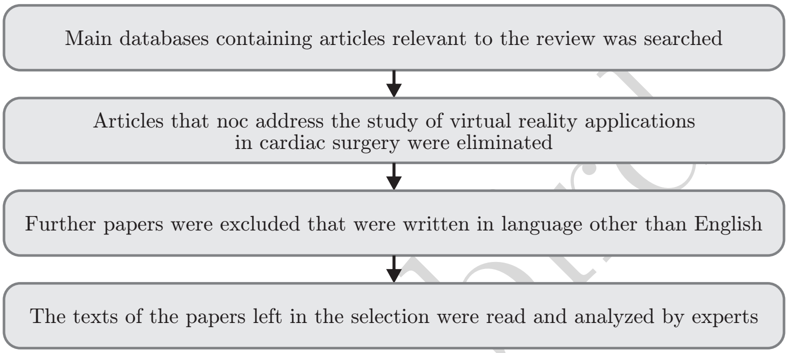

Figure 1. Methodology of the review

Despite the apparent popularity of the topic of VR use in cardiac surgery, only 47 articles published between 2002 and 2022 met the inclusion criteria for the review (Fig. 2).

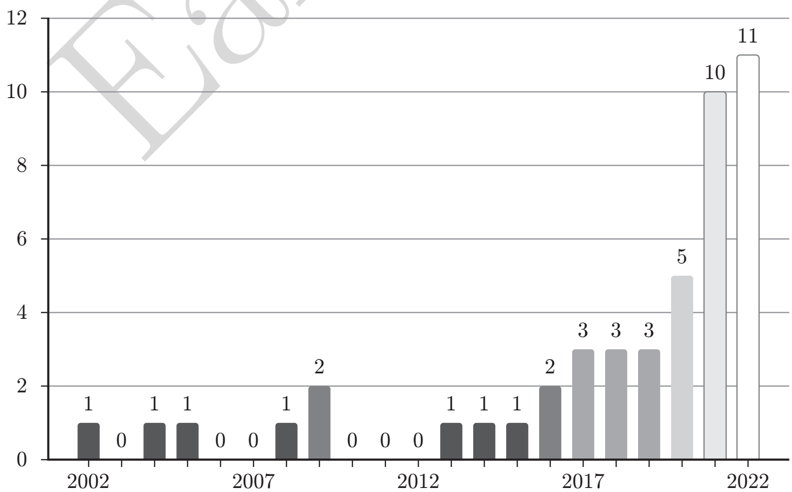

Figure 2. Number of publications selected to the review

Analyzing Figure 2, it can be seen that the number of articles and scientific studies on VR-based solutions in cardiac surgery is constantly growing. This means that the use of modern technologies in cardiac surgery is significant and brings better and better results. Hence the interest of scientists in this subject. Next we will describe the VR methods that are currently used in cardiac surgery based on a review of the available literature on this subject.

3. VR-based Methods in Medicine

Nowadays the VR processes are being used in an increasing number of daily life activities, fully or partially replacing real processes [19]. Technological developments in the area of VR creation offer opportunities to use this technological advance in many areas of science, economy and social activity. Although VR is a relatively young field, medical science and clinical practice have already learned to benefit from it in the areas of didactics, diagnosis and patient treatment [2,15]. As far as didactics is concerned, VR allows medical professionals to improve their skills by being able to repeat activities repeatedly with rare clinical cases. At the initial training stage, e.g. for surgeons, it allows a greater margin for errors to be made without affecting the patient. An additional aim of such training is to improve automatic coordination between the monitor and manual procedures. Such an opportunity allows one to focus on the important aspects and not, for example, on what the hands are currently doing [13].

VR has a wide range of applications in neurological rehabilitation – mainly due to the ease of mapping the natural environment, creating specific movement patterns and attractive exercises in which the patient actively participates [16]. Patients learn to use a specific activity in the virtual world and then, with the active supervision of the therapist, transfer specific movement patterns to everyday activities [69]. VR can also support and enhance basic forms of treatment that require repetitive exercises that are tedious and often boring from the patient's point of view. In the case of cardiac patients – those with coronary heart disease – improvements in the mental joint have been demonstrated when classical cardiac rehabilitation is supplemented with VR elements [36]. In the cognitive sphere, virtual reality is gaining an advantage over the classic form of pen-and-paper-based neuropsychological therapy [102]. Virtual reality makes it possible to replicate real-life situations with real-time images of the patient. The course and progress of therapy can also be easily reported, showing the patient the effects of the therapy, which facilitates further diagnosis and modification of the therapy plan by the clinician. Importantly, due to the nature of the therapy provided, virtual reality can be carried out remotely, e.g. in chronic cases where it is difficult for the patient to reach the centre, with simultaneous control of the therapy by the therapist. Additionally, the costs of this form of rehabilitation have been shown to be lower than its traditional form. [52].

4. VR-based Methods in Cardiac Surgery

Among reviewed articles only four were review-type articles. Meta-analyses and comprehensive reviews are lacking. Intractable VR allows 3D models of complex intracardiac and extracardiac anatomy to be viewed, even in infants, the ability for users to define their own views based on existing medical diagnostic data. This provides a useful complement to traditional preoperative planning methods, the opportunity for group discussion by the treatment team (including cardiologists and cardiac surgeons), reliability, rapid learning, cost-effectiveness and ease of use [65]. Medical simulation in cardiac surgery, including VR-based simulation, improves trainee learning and performance by allowing repeated training until the required high level of mastery of specific cardiac competencies is achieved, but further research is required on how this translates to the performance of tasks in the operating theatre in relation to a real patient. Cardiac surgery simulation is not yet part of the training program, simulators are available for some tasks and procedures, but based on three different types of simulators [91]:

1. full manikin simulators,
2. partial task trainers,
3. virtual reality systems or combinations of these, including 3D-printed components of a specific patient's cardiovascular system.

There is a strong interest in Head-Mounted Displays (HMDs) and smart glasses in cardiac and vascular surgery for the education of surgeons and for surgical practice, but further technical improvements and clinical trials on large groups are needed for their fuller implementation [47]. Early mobilisation of patients in the post-operative period of cardiac surgery either, in the immediate post-operative period or on the first postoperative day, has positive results. It uses early bedside activity, VR, progressive mobilisation, resistance exercises, cycle ergometer and walking protocols, rather not personalised, low progressive intensity, twice a day for up to 30 minutes [5].

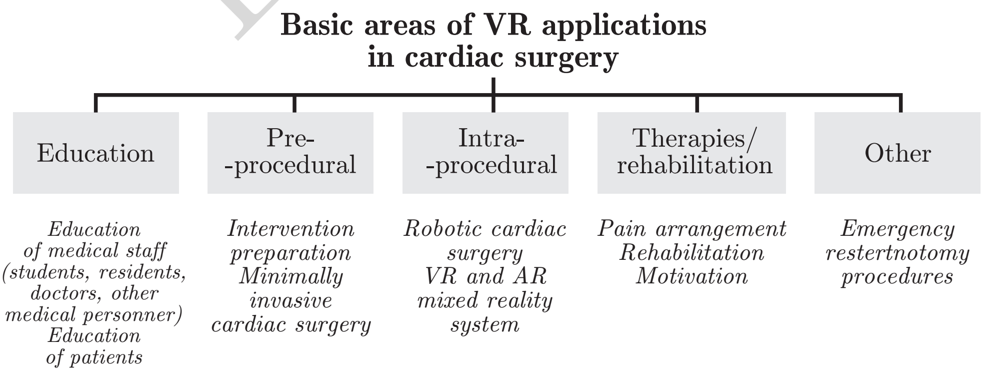

Figure 3. Main areas of VR application in cardiac surgery according to the review.

From the point of view of cardiac surgery, VR involves a computer-generated three-dimensional simulation that the user (surgeon, student, their entire team – each from their own perspective) sees and manipulates [9,64]. Research to date shows that VR improves teaching, but does not completely replace traditional teaching methods [64, 89]. Furthermore, learning with 360° VR video is more effective than learning with 2D video, i.e. realism is key [9]. Within the computer-based teaching module (CBTM), three levels of design were identified [48]:

1. **global level** (goal management, framing, minimising technical load);
2. **rhetorical level** (optimising modalities, making modalities explicit, scaffolding, development, spaced repetition);
3. **specific level** (text management, device management).

Figure 3 shows the main application areas of VR-solutions in cardiac surgery. For each of these scientific areas, a review of the latest articles was carried out, and below we present the state-of-art results.

4.1. VR-supported Education of Medical Professionals

The complexity of cardiac surgery requires ongoing education and training, with an audience of different people and their teams: doctors (cardiologists, cardiac surgeons, anaesthetists), students, as well as patients and their families/carers [4, 8, 18, 66, 74]. Education of medical specialists with the use of VR has its origins in the 90s of the XX century [39], while the beginnings of education in the field of the cardiovascular system using VR date back to the beginning of this century [17,18]. From the outset, VR has been evaluated as a technology with the potential to support the teaching and assessment of clinical skills of students, residents and doctors. It has fostered the development of medical simulation centres, among others, as it allows various degrees of 'immersion' of trainees in an environment reflecting real clinical situations with such a high degree of accuracy that the clinical skills (diagnostic, therapeutic, etc.) thus acquired are later transferred to patients [73]. The multiplicity of scenarios allow more scenarios (variations in anatomy, pathology, interventions, complications) to be practised in this way than in the real world at the same time (e.g. because there are not enough patients to train). This applies primarily to young resident doctors who should train as much as possible and have contact with various cases, so that in the future they can cope with any situation, even with difficult operations [92]. What's more, the trainees can repeat them in VR many times in different variants without harming the patients until they are completely mastered. Cardiac surgery requires an integrated system for teaching both, from the point of view of content (multimedia elements, their decomposition and description possibilities within teaching scenarios) and information technology within the chosen educational environment. This allows not only the integration in practice of the knowledge and experience acquired during traditional forms of teaching, but also the seamless movement of the trainer across different levels of teaching, student sophistication or even (in medical simulation) the integration of team activities [18]. During COVID-19, the use of simulators for cardiac surgery allowed for continuous practice of doctors, so that after the pandemic they could go to surgery without unnecessary interruption in training [58]. Interactive VR available locally and via the World Wide Web is used both to teach, analyse and describe cardiac anatomy and to prepare surgical techniques. Their advantages over traditional teaching techniques include a realistic rendering of the sequence of events and spatial considerations during a cardiac surgical procedure [17]. Such solutions are widely accepted. Noorali et al. proposed in-house Pakistani solution (simulation lab) providing interdisciplinary VR-based training for promising cardiac surgeons [63].

The use of VR in education is also of utmost importance in the paediatric cardiac intensive care unit [72]. Children, due to their size, are much more difficult cardiac patients and greater precision is required during surgery. Without proper doctor training, performing a cardiac surgery on a child can result in many complications during the procedure. The use of VR-based technology during the doctor's education gives him better training facilities and greater skills to perform such complex operations.

Advances in VR and related devices such as endoscopes and cardiac robots could enable the development of new therapies for severe heart disease. This will require the acquisition of new skills, also on simulators, as has been the case so far, e.g. when learning stimulation and ablation [84].

4.2. VR-supported Education for Patients and their Families

VR can be used as a tool not only to educate doctors and medical staff, but also patients. The use of this technology allows the patient to prepare for surgery and understand the entire process that awaits him. The use of VR increases the understanding, knowledge or comprehension of the patient. An additional advantage of using VR technology is increased satisfaction and reduced anxiety among patients. It also affects the patient's positive perception of the activities performed by the medical personnel [44].

VR becomes an important motivation and learning tool for patients in cardiac surgery [5]. Patients undergoing rehabilitation after cardiac surgery have different needs and preferences. They need a sense of security and seek additional advice. Any e-learning program, including one based on VR, reduces their uncertainty and improves overall mental well-being which supports their faster recovery [28]. Similar VR-based patients' educational programs are studied in obesity and diabetes [12].

4.3. VR-based Intervention Preparation and Minimally Invasive Cardiac Surgery

We decided to separate the planning of the procedure from teaching medical specialists due to its specificity, target group and the importance of benefits that this area of development of VR systems supporting cardiac surgeons may bring, especially in difficult and atypical cases [61, 65]. Successful cardiac surgery procedures require a thorough understanding of the complex anatomy and pathophysiology of the cardiovascular system. This improves the spatial and temporal understanding of pathological changes and their dynamics when using surgical access and performing the procedure. In a broader context, such an approach accelerates the preparation of procedures, which is important in a large number of urgent cases, when the time to prepare the team is short and the procedure saves the patient's life [41]. It is also an important issue in the case of unusual or complex cases where the use of VR before surgery may modify a surgical procedure [61].

Wierzbicki et al. proposed in 2004 Virtual Cardiac Surgery Planning (VCSP) ([96]) a VR model of the chest made individually for each patient from preoperative medical imaging (CT, MRI) . The requirements for such solutions include, above all, adaptability, ease of use and a fairly high degree of accuracy (MSE approx. 1 mm), also in reflecting the dynamics of the operation, for increased reliability in training, planning and conducting cardiac surgery. In addition, limitations due to patients safety, the need for full coverage of the heart with dynamic images from X-rays and angiograms, and the need to use an endoscope to navigate the instruments must be taken into account [68]. In their approach, a static heart model is created by segmenting one of the frames (an image, i.e. a 4D data set), and then based on the remaining frames, the dynamics extracted from the remaining frames of the image is added based on a proprietary algorithm. A similar solution based on CT in robotic cardiac surgery was shown by Ivanov et al. in [33]. VR-based integration of CT scans and endoscopic images showed mean spatial error 1.4 mm and time discrepancy in the range of $50 - 100$ ms [83]. The above-mentioned parameters improve with the development of technology.

The 3D cardiographic virtual endoscopy based on MRI and CT scans can be useful in cardiac surgery of children. It achieves diagnostic accuracy ranging from $92.4\% - 98.7\%$ [97]. Vigil et al. showed in [90] that VR modelling (based on MRI) of the septal pathway and subsequent development of septal templates and visualisation of the access pathway can be beneficial in the preoperative planning of complex double-outlet right ventricle repairs. Ghosh et al. in [22] demonstrated the usefulness of VR-based cardiac preparation in a pediatric center with high patient traffic. It uses MRI or CT images to segment the image and transform it into VR with FDA-approved software. Interestingly, in addition to VR, 3D printed models and digital 2D models are also used, with the option of surgical repair made in CAD are designed digitally using proprietary open source computer-aided (CAD) modeling tools. The legitimacy of using the above-mentioned Clinical modeling is shown by statistics: in 3 consecutive years (2018-2021) the demand for it in children has tripled, and in 2020 3, 4 and 5 STAT categories were requested in more than 25% of cases. It is worth noting that the most common indications for modeling in children were complex 2-chamber repair (31%) and repair of multiple defects in the interventricular septum (12%) [22]. In the case of children, the accuracy of the computer model is 0.54 mm and the accuracy of 3D printing is 0.05 mm compared to the digital equivalent [67]. A very interesting option is the transformation of 3D echocardiographic and cardiac CT data into VR models of higher diagnostic quality, with more accurate measurements and faster navigation [62]. The difference is in the time of obtaining the finished model, where the median time of post-processing VR (DIVA i.e. directly applicable MRI data without intermediate segmentation) was 5 min compared to $8 - 12$ h for 3D printed models [71]. So the time advantage of VR-based models is obvious. The VR systems supporting both preoperative imaging (based on e.g. MRI) and intraoperative in vivo (based on e.g. ultrasound) are more and more often integrated with models of surgical instruments, offering 4.8 mm RMS alignment accuracy [49–51]. The observed difficulties in the interaction of surgeons with the VR environment result from their speed of orientation, insufficient depth information and delegation of view control with an emphasis on the efficiency of the user and his workload [53].

4.4. VR-based Robotic Cardiac Surgery

The last 20 years have brought significant advances in the field of automated minimally invasive cardiac surgery being a safer and more effective solution for some patients from traditional cardiac surgery [33]. In 1998, the Da Vinci robotic system was first used for cardiothoracic surgery [34, 95]. Undoubtedly, cardio-surgical robots have increased the capabilities and precision of surgeons, especially in the areas of mitral valve surgery, closure of the atrial septal defect, and direct coronary artery bypass surgery [31, 32].

A study carried out by Chiu et al. ([10]) showed different effectiveness of active involvement of peer observation, in addition to expert demonstration in VR tasks, such as camera control, stratification and switching, energy and seam sponge in da Vinci skill simulators. The effectiveness of such VR observation still requires optimization in order to ensure the best possible learning outcomes. Interestingly, medical students (females) achieved better results in the VR task involving a spongy suture and obtained more stitches, which indicates the need to differentiate training depending on gender [11]. The usefulness of VR-based training in preparation for the use of the da Vinci robot in trainees was also shown by Gleason et al. [23].

According to the results of a randomised controlled trial (RCT) conducted by Valdis et al. [86, 87], it was proven that the VR helps with cost-effective, high-performance simulation exercises in cardiac robotics.

During the operation, mixed reality systems combining VR and AR are used. An example is the system of Sentiar, Inc., St. Louis, MO deployed on a Microsoft HoloLens (Microsoft Inc., Redmond, WA) [55, 81]. During the operation, the doctor uses a headset, where he has a 3D visualisation of the patient's cardiac system and controls it hands-free. The doctor can get information about the location of the catheter in real time.

4.5. VR-based Pain Management During Cardiac Surgery

VR-based pain management in patients after cardiac surgery alleviates vital parameters, reduces discomfort and postoperative stress [60]. But more research is needed in order to determine if it may occur and what approach to pain and anxiety, for example, in intensive care units [46]. VR also allows you to effectively reduce pre-operative anxiety without the use of pharmacological agents [1, 29, 94]. Studies have observed the effect of using VR for postoperative rehabilitation on reducing the use of analgesics in hospitals [57, 85]. VR works well for pain relief, especially after cardiac surgery due to the so-called Gate Theory of Attention. According to this theory, if the patient's attention is diverted and occupied with other activities, he will forget about the pain he is feeling [35]. This mechanism is used in the case of the VR-based tool to reduce pain.

4.6. VR-Supported Cardiac Rehabilitation of Patients

There is a widespread belief that VR technologies can provide controlled, multi-sensory, interactive 3D stimulus environments that engage patients in interventions and measure, record and motivate required human performance. In particular, this can be achieved by promoting desired health behaviours through motivational reinforcement, personalised learning methods and social networks. Moreover, this can be effective even in the case of increasing rates, high prevalence and adverse consequences of disease [12]. VR-based rehabilitation compared to the traditional approach in the control group showed better functional outcomes in patients undergoing cardiac surgery, expressed in outcomes of the Functional Independence Measure (FIM), the 6 minute walk test (6 MWT), and the Nottingham Health Profile (NHP) [7]. To date, post-operative cardiac rehabilitation programs have a number of limitations related both to patients' musculoskeletal problems themselves and more broadly to psychological or existential issues related to lifestyle and health responsibilities [27, 28, 80]. Wider implementation of VR may help to better design such future programs [28].

VR technology can be used during various stages of rehabilitation and many of its features allow to qualify it as a complete rehabilitation tool. In the process of rehabilitation, a very important aspect is the patient's motivation to work on recovery. Tedious exercises can demotivate patients, who therefore adhere less to the recommendations. VR technology increases motivation and makes exercises more interesting and accessible to the patient. Especially in connection with video games [20]. Patients using interactive virtual reality are more active, feel less pain and recover faster after cardiac surgery.

4.7. Other Applications of VR in Cardiac Surgery

VR simulation for purposes of training of cardiopulmonary resuscitation as far as emergency resternotomy procedures after cardiac surgery were developed by Sadeghi et al [77]. The proposed solution is at the proof of concept stage and requires further research . However, the use of VR in cardiac surgery may expand in the coming years to various applications. Virtual reality is also used to create 3D images of cardiac anatomy and VR connects with AG to mixed reality, which creates even more application possibilities [55, 71].

5. Discussion

Overall, the results of our review confirm the opinion on the prospect of research into the applications of VR in cardiac surgery. We found only one article questioning VR support for cardiac surgery. It concerns the 3D diagnosis of congenital atrioventricular valves, yet the authors' doubts do not concern the value of the method itself, but whether its validity is certain at this early stage of development. The authors do not deny that the method itself, when refined, can improve surgeons' understanding of the nature of the defect and help them formulate a repair strategy [59]. Such discussions are desired in science and should take place at such early stages in the development of individual solutions, allowing scientists and engineers to improve them, and clinicians to choose the best one. At the same time, two competing technologies were indicated: Augmented Reality (AR) [70,76] and 3D printing [38,42,98,100]. This has important implications in terms of the directions of further comparative research between the above-mentioned three main technologies.

As directions for further research, it is crucial to define the differences between teaching using VR (also AR) and traditional quality teaching methods, as well as training methodologies combining/interweaving the above mentioned teaching modalities [6, 64]. Combining multi-modal sensory data and emotion assessment are also available, including analysis and simulation by artificial intelligence [6]. A very important direction of further research is the recognition of clinical needs – the coordination of knowledge and experience of engineers, scientists and clinicians may lead to the development of new fields of VR applications in previously unexplored areas of cardiac surgery, which we may not even know are within reach (e.g. cardiac surgery), preventive, micro- or nanorobotics, cardiosurgical neuroprosthetics based on bioMEMS and bioNEMS). Clinical 3D modelling must be integrated with the pre-operative care of patients with heart defects, and the demand for these services is growing rapidly [22, 43].The use of VR in cardiac surgery is not just in one area and the benefits may be subject to synergistic effects. Further work is needed to fully demonstrate the clinical benefits and improved outcomes in post-cardiac surgery patients as a result of VR-based methods and/or tools.

An interesting area of VR applications is prehabilitation [14, 30], i.e. preparing patients for cardiac surgery. Each such procedure, no matter how minimally invasive, is a challenge for the body. Hence the body needs to be properly prepared for it: physically (diet, activity) and mentally (positive attitudes, motivation to change your lifestyle to a healthier one as part of medicine). Hirota proposed that VR-prehabilitation may be a promising tool for the prevention of postoperative delirium POD [30]. This will turn cardiac interventions into a type of personalised targeted therapy to avoid relapse.

The VR/AR-based curriculum platform should be standardised to benchmark the development of basic robotic skills, provide common interdisciplinary surgical education and objectify student achievement. There is also a lack of studies and publications on the standardisation of management in AV/AR-assisted cardiac surgery.

Further large-scale randomised clinical trials on large homogeneous groups of patients are needed to develop standards. These will increase as the technology itself becomes more widespread.

6. Conclusions

The application of VR technology to cardiac surgery has many aspects and development possibilities. Taking into account the current advancement of work in this field, it can be expected that in the near future, training of doctors and residents will be based on VR-based virtual and real cases. Cardiac surgery simulation should be a part of the training program. Combining VR with MRI and CT imaging can also create models of hearts in difficult cases on which the surgeon can practise before starting surgery on the patient. Another aspect in the VR-based support of cardiac surgery will be the development of cardiac robots using VR to perform semi-automatic or automatic surgery. The next step will be carrying out remote surgery using VR imaging. The specialist will not have to be physically in the same place as the patient to participate in cardiac surgery. Using VR and robots, the doctor will see what is happening during the operation, on this basis, will be able to decide on the next steps of the operation and will perform the surgery procedure using this robot. While pre- and post-operative VR-based solutions help patients with rehabilitation and pain management. This approach will certainly influence the patients' well-being and faster return to health.

Currently, VR and AR are used in all the above-mentioned aspects of cardiac surgery. In combination with Industry 4.0 technologies, the health care system is improved and Healthcare 4.0 systems are created. Such systems take advantage of various technologies to improve patient health care. Currently, both VR and AR applications are being considered. Both technologies complement each other and in the near future there will probably be solutions based on one or the other technology implemented in care systems during cardiac surgery.

To sum up the field of VR/AR applications in cardiac surgery is growing rapidly, and researchers, medical professionals and technology developers continue to explore innovative ways to use immersive technologies to improve surgical outcomes and patient care:

1. surgical training and simulation: enhanced training modules and integration of haptic feedback,
2. patient-specific models based on medical imaging data for pre-operative planning with AR overlay in surgery (showing 3D reconstructions, vital signs or navigation cues and other data,
3. telemedicine and remote support: remote consultations (providing real-time guidance and support) and training support in remote areas with limited access to medical expertise.
4. data integration and analysis and visualisation in a convenient form for the surgeon/team, as well as decision support systems.

VR-based solutions in cardiac surgery are useful both for medical specialists at various levels of professional development and for the patients themselves. The VR-based curriculum platform should be standardised to compare the development of basic robotic skills, provide a common interdisciplinary surgical education, and objectify student achievement. The new lifestyle required from cardiac surgery patients is easier to implement thanks to VR-based educational and motivational tools. However, it is necessary to develop the above-mentioned tools and compare their effectiveness with AR. With the aforementioned reasons, interdisciplinary collaboration between scientists, clinicians and engineers is necessary.

References

[1] Aardoom JJ ., Hilt AD ., Woudenberg T., Chavannes N., Atsma D.: A Preoperative Virtual Reality App for Patients Scheduled for Cardiac Catheterization: Pre-Post Questionnaire Study Examining Feasibility, Usability, and Acceptability, *JMIR Cardio*, vol. 6(1), p. e29473, 2022.

[2] Alfalah F., Falah J., Alfalah T., Elfalah M., Muhaidat N., Falah O.: A Comparative Study Between a Virtual Reality Heart Anatomy System and Traditional Medical Teaching Modalities, *Virtual Reality*, vol. 23, pp. 229–234, 2019.

[3] Alonzo M., AnilKumar S., Roman B., Tasnim N., Joddar B.: 3D Bioprinting of cardiac tissue and cardiac stem cell therapy, *Translational Research*, vol. 211, pp. 64–83, 2019.

[4] Borger M.: The future of cardiac surgery training: A survival guide, *J Thorac Cardiovasc Surg*, vol. 154(3), pp. 994–995, 2017.

[5] Borges M., Borges D., Ribeiro MO.; Lima L., Macedo K., Nina V.: Early Mobilization Prescription in Patients Undergoing Cardiac Surgery: Systematic Review, *Braz J Cardiovasc Surg*, vol. 37(2), pp. 227–238, 2022.

[6] Bălan O., Moise G., Moldoveanu A., Leordeanu M., Moldoveanu F.: An Investigation of Various Machine and Deep Learning Techniques Applied in Automatic Fear Level Detection and Acrophobia Virtual Therapy, *Sensors*, vol. 20, p. 496, 2020.

[7] Cacau Lde A., Oliveira G., Maynard L., Araójo Filho A., Silva W.J., Cerqueria Neto M., Antoniolli A., Santana-Filho V.: The use of the virtual reality as intervention tool in the postoperative of cardiac surgery, *Rev Bras Cir Cardiovasc*, vol. 28(2), pp. 281–9, 2014.

[8] Chakravarthy M.: Future of awake cardiac surgery, *J Cardiothorac Vasc Anesth*, vol. 28(3), pp. 771–7, 2014.

[9] Chao Y., Chuang H., Hsin L., Kang C., Fang T., Li H., Huang C., Kuo T., Yang C., Shyu H., Wang S., Shyu L., L.A. L.: Using a 360° Virtual Reality or 2D Video to Learn History Taking and Physical Examination Skills for Undergraduate Medical Students: Pilot Randomized Controlled Trial, *JMIR Serious Games*, vol. 9(4), p. e13124, 2021.

[10] Chiu H., Kang Y., Wang W., Chen C., Hsu W., Tseng M., Wei P.: The Role of Active Engagement of Peer Observation in the Acquisition of Surgical Skills in Virtual Reality Tasks for Novices, *J Surg Educ*, vol. 76(6), pp. 1655–1662, 2019.
[11] Chiu H., Kang Y., Wang W., Tong Y., Chang S., Fong T., Wei P.: Gender differences in the acquisition of suturing skills with the da Vinci surgical system, *J Formos Med Assoc*, vol. 119(1 Pt 3), pp. 462–470, 2020.
[12] Ershow A., Peterson C., Riley W., Rizzo A., Wansink B.: Virtual reality technologies for research and education in obesity and diabetes: research needs and opportunities, *J Diabetes Sci Technol*, vol. 5(2), pp. 212–24, 2011.
[13] Eysenck M., Keane M.: Attention and performance limitations. Foundations of cognitive psychology: core readings, *MIT Press, Cambridge, MA*, pp. 363–398, 2002.
[14] Fernandez-Costa D., Gomez-Salgado J., Castillejo del Rio A., Borrallo-Riego A., Guerra-Martin M.D.: Effects of prehabilitation on functional capacity in aged patients undergoing cardiothoracic surgeries: a systematic review. In: *Healthcare*, vol. 9(11), p. 1602, Multidisciplinary Digital Publishing Institute, 2021.
[15] Fidurski K., Falkowski-Gilski P.: Nauka w swiecie cyfrowym okiem mlodego inzyniera - poczatki techniki wirtualnej rzeczywistosci, *Pismo PG*, vol. 1, pp. 30–32, 2022.
[16] Fluet G., Deutsch J.: Virtual Reality for Sensorimotor Rehabilitation Post-Stroke: The Promise and Current State of the Field, *Curr Phys Med Rehabil Rep*, vol. 1(1), pp. 9–20, 2013.
[17] Friedl R., Preisack M., Klas W., Rose T., Stracke S., Quast K., Hannekum A., Godje O.: Virtual reality and 3D visualizations in heart surgery education, *Heart Surg Forum*, vol. 5(3), pp. E17–21, 2002.
[18] Friedl R., Preisack M., Schefer M., Klas W., Tremper J., Rose T., Bay J., Albers J., Engels P., Guilliard P., Vahl C., Hannekum A.: CardioOp: an integrated approach to teleteaching in cardiac surgery, *Stud Health Technol Inform*, vol. 70, pp. 76–82, 2000.
[19] Furmanek W.: Symulacje, gry symulacyjne w dydaktyce. Dydaktyka Informatyki, Modelowanie i symulacje komputerowe, *Wyd UR, Rzeszêw*, 2010.
[20] García-Bravo S., Cuesta-Gómez A., Campuzano-Ruiz R., López-Navas M.J., Domínguez-Paniagua J., Araújo-Narváez A., Barreñada-Copete E., García-Bravo C., Flórez-García M.T., Botas-Rodríguez J., *et al.*: Virtual reality and video games in cardiac rehabilitation programs. A systematic review, *Disability and Rehabilitation*, vol. 43(4), pp. 448–457, 2021.
[21] Gendia A., Rehman M., Cota A., Gilbert J., Clark J.: Can virtual reality technology be considered as a part of the surgical care pathway?, *The Annals of The Royal College of Surgeons of England*, vol. 105(1), pp. 2–6, 2023.
[22] Ghosh R., Jolley M., Mascio C., Chen J., Fuller S., Rome J., Silvestro E., KK. W.: Clinical 3D modeling to guide pediatric cardiothoracic surgery and intervention using 3D printed anatomic models, computer aided design and virtual reality, *3D Print Med*, vol. 8(1), p. 11, 2022.

[23] Gleason A., Servais E., Quadri S., Manganiello M., Cheah Y., Simon C., Preston E., Graham-Stephenson A., Wright V.: Developing basic robotic skills using virtual reality simulation and automated assessment tools: a multidisciplinary robotic virtual reality-based curriculum using the Da Vinci Skills Simulator and tracking progress with the Intuitive Learning platform, *J Robot Surg*, vol. doi: 10.1007/s11701-021-01363-9, 2022.

[24] Gokce C., Gurcan C., Delogu L.G., Yilmazer A.: 2D materials for cardiac tissue repair and regeneration, *Frontiers in Cardiovascular Medicine*, vol. 9, p. 802551, 2022.

[25] Gooding P.M., Clifford D.M.: Semi-automated care: Video-algorithmic patient monitoring and surveillance in care settings, *Journal of bioethical inquiry*, vol. 18(4), pp. 541–546, 2021.

[26] Grab M., Hopfner C., Gesenhues A., Konig F., Haas N.A., Hagl C., Curta A., Thierfelder N.: Development and evaluation of 3D-printed cardiovascular phantoms for interventional planning and training, *JoVE (Journal of Visualized Experiments)*, vol. 167, p. e62063, 2021.

[27] Hansen T., Zwisler A., Berg S., Sibilitz K., Buus N., A. L.: Cardiac rehabilitation patients' perspectives on the recovery following heart valve surgery: a narrative analysis, *J Adv Nurs*, vol. 72(5), pp. 1097–108, 2016.

[28] Hansen T.B., Berg S.K., Sibilitz K.L., Zwisler A.D., Norekvål T.M., Lee A., Buus N.: Patient perceptions of experience with cardiac rehabilitation after isolated heart valve surgery, *European Journal of Cardiovascular Nursing*, vol. 17(1), pp. 45–53, 2018.

[29] Hendricks T., Gutierrez C., Stulak J., Dearani JA.; Miller J.: The Use of Virtual Reality to Reduce Preoperative Anxiety in First-Time Sternotomy Patients: A Randomized Controlled Pilot Trial, *Mayo Clin Proc*, vol. 95(6), pp. 1148–1157, 2020.

[30] Hirota K.: Preoperative management and postoperative delirium: the possibility of neuroprehabilitation using virtual reality, *Journal of anesthesia*, vol. 34(1), pp. 1–4, 2020.

[31] Ishikawa N., Watanabe G.: Robot-assisted cardiac surgery, *Ann Thorac Cardiovasc Surg*, vol. 21(4), pp. 322–8, 2015.

[32] Ishikawa N., Watanabe G.: Ultra-minimally invasive cardiac surgery: robotic surgery and awake CABG, *Surg Today*, vol. 45(1), pp. 1–7, 2015.

[33] Ivanov N., Green D., Guy T.: Integrate imaging approach for minimally invasive and robotic procedures, *J Thorac Dis*, vol. 9(Suppl4), pp. S264–S270, 2017.

[34] Jin Z.: Clinical application of Da Vinci surgical system in China, *Zhongguo Yi Liao Qi Xie Za Zhi*, vol. 38(1), pp. 47–9, 2014.

[35] Jones T., Moore T., Choo J.: The impact of virtual reality on chronic pain, *PloS one*, vol. 11(12), p. e0167523, 2016.

[36] Jozwik S., Wrzeciono A., Cieslik B., Szczepanska-Gieracha J., R. G.: The Use of Virtual Therapy in Cardiac Rehabilitation of Male Patients with Coronary Heart Disease: A Randomized Pilot Study, *Healthcare*, vol. 10(4), p. 745, 2022.

[37] Kamel Boulos M.N., Zhang P.: Digital twins: from personalised medicine to precision public health, *Journal of Personalized Medicine*, vol. 11(8), p. 745, 2021.

[38] Kappanayil M., Koneti N., Kannan R., Kottayil B., Kumar K.: Three-dimensional-printed cardiac prototypes aid surgical decision-making and pre-operative planning in selected cases of complex congenital heart diseases: Early experience and proof of concept in a resource-limited environment, *Ann Pediatr Cardiol*, vol. 10(2), pp. 117–125, 2017.

[39] Kaufman D., Bell W.: Teaching and assessing clinical skills using virtual reality, *Stud Health Technol Inform*, vol. 39, pp. 467–72, 1997.

[40] Kennedy C.W., Hu T., Desai J.P., Wechsler A.S., Kresh J.Y.: A novel approach to robotic cardiac surgery using haptics and vision, *Cardiovascular Engineering: An International Journal*, vol. 2, pp. 15–22, 2002.

[41] Kim B., Nguyen P., Loke Y.H., Cleveland V., Liu X., Mass P., Hibino N., Olivieri L., Krieger A., *et al.*: Virtual Reality Cardiac Surgical Planning Software (CorFix) for Designing Patient-Specific Vascular Grafts: Development and Pilot Usability Study, *JMIR cardio*, vol. 6(1), p. e35488, 2022.

[42] Kiraly L., Shah N., Abdullah O., Al-Ketan O., Rowshan R.: Three-Dimensional Virtual and Printed Prototypes in Complex Congenital and Pediatric Cardiac Surgery-A Multidisciplinary Team-Learning Experience, *Biomolecules*, vol. 11(11), p. 1703, 2021.

[43] Krasemann T., Branstetter J.: Virtual Reality Treatment Planning for Congenital Heart Disease, *JACC Case Rep*, vol. 3(14), pp. 1584–1585, 2021.

[44] van der Kruk S.R., Zielinski R., MacDougall H., Hughes-Barton D., Gunn K.M.: Virtual reality as a patient education tool in healthcare: A scoping review, *Patient Education and Counseling*, 2022.

[45] Kumar A., Krishnamurthi R., Nayyar A., Sharma K., Grover V., Hossain E.: A novel smart healthcare design, simulation, and implementation using healthcare 4.0 processes, *IEEE access*, vol. 8, pp. 118433–118471, 2020.

[46] Laghlam D., Naudin C., Coroyer L., Aidan V., Malvy J., Rahoual G., Estagnasiä P., Squara P.: Virtual reality vs. Kalinox£ for management of pain in intensive care unit after cardiac surgery: a randomized study, *Ann Intensive Care*, vol. 11(1), p. 74, 2021.

[47] Lareyre F., Chaudhuri A., Adam C ., Carrier M., Mialhe C., Raffort J.: Applications of Head-Mounted Displays and Smart Glasses in Vascular Surgery, *Ann Vasc Surg*, vol. 75, pp. 497–512, 2021.

[48] Lau K.: Computer-based teaching module design: principles derived from learning theories, *Med Educ*, vol. 48(3), pp. 247–54, 2014.

[49] Linte C., Moore J., Wedlake C., Bainbridge D., Guiraudon G., Jones D., Peters T.: Inside the beating heart: an in vivo feasibility study on fusing pre- and intra-operative imaging for minimally invasive therapy, *Int J Comput Assist Radiol Surg*, vol. 4(2), pp. 113–23, 2009.

[50] Linte C., Moore J., Wiles A., Wedlake C., Peters T.: Virtual reality-enhanced ultrasound guidance: a novel technique for intracardiac interventions, *Comput Aided Surg*, vol. 13(2), pp. 82–94, 2008.

[51] Linte C., White J., Eagleson R., Guiraudon G., Peters T.: Virtual and augmented medical imaging environments: enabling technology for minimally invasive cardiac interventional guidance, *IEEE Rev Biomed Eng*, vol. 3, pp. 25–47, 2010.

[52] Llorens R., Noe E., Colomer C., Alcaniz M.: Effectiveness, usability, and cost-benefit of a virtual reality-based telerehabilitation program for balance recovery after stroke. A randomized controlled trial, *Arch Phys Med Rehabil*, vol. 96(3), pp. 418–25, 2015.

[53] Lo J., Moore J., Wedlake C., Guiraudon G., Eagleson R., Peters T.: Surgeon-controlled visualization techniques for virtual reality-guided cardiac surgery, *Stud Health Technol Inform*, vol. 142, pp. 162–7, 2009.

[54] Maciolek J., Wasek W., Kaminski B., Piotrowicz K., Krzesinski P.: The impact of mobile virtual reality–enhanced relaxation training on anxiety levels in patients undergoing cardiac rehabilitation, *Kardiologia Polska (Polish Heart Journal)*, vol. 78(10), pp. 1032–1034, 2020.

[55] Maresky H., Oikonomou A., Ali I., Ditkofsky N., Pakkal M., Ballyk B.: Virtual reality and cardiac anatomy: Exploring immersive three-dimensional cardiac imaging, a pilot study in undergraduate medical anatomy education, *Clinical Anatomy*, vol. 32(2), pp. 238–243, 2019.

[56] Maynard L.G., de Menezes D.L., Lião N.S., de Jesus E.M., Andrade N.L.S., Santos J.C.D., da Silva Júnior W.M., Bastos K.d.A., Barreto Filho J.A.S.: Effects of exercise training combined with virtual reality in functionality and health-related quality of life of patients on hemodialysis, *Games for health journal*, vol. 8(5), pp. 339–348, 2019.

[57] McFarland M., Zelaya N., Hossain G., Hicks D., McLauchlan L.: Pain Mitigation Through Virtual Reality Applications. In: *2019 IEEE International Symposium on Measurement and Control in Robotics (ISMCR)*, pp. A2–5, IEEE, 2019.

[58] McKechnie T., Levin M., Zhou K., Freedman B., Palter V.N., Grantcharov T.P.: Virtual surgical training during COVID-19: operating room simulation platforms accessible from home, *Annals of surgery*, vol. 272(2), p. e153, 2020.

[59] Moscatiello M., Lo Rito M.: Commentary: Virtual reality 3-dimensional imaging of atrioventricular valves: A tool for surgeons or a toy for engineers?, *JTCVS Tech*, vol. 7, pp. 278–279, 2021.

[60] Mosso-Vçzquez J., Gao K., Wiederhold B., Wiederhold M.: Virtual reality for pain management in cardiac surgery, *Cyberpsychol Behav Soc Netw*, vol. 17(6), pp. 371–8, 2014.

[61] Napa S., Moore M., Bardyn T., *et al.*: Advancing cardiac surgery case planning and case review conferences using virtual reality in medical libraries: evaluation of the usability of two virtual reality apps, *JMIR human factors*, vol. 6(1), p. e12008, 2019.

[62] Narang A., Hitschrich N., Mor-Avi V., Schreckenberg M., Schummers G., Tiemann K., Hitschrich D., Sodian R., Addetia K., Lang R., Mumm B.: Virtual Reality Analysis of Three-Dimensional Echocardiographic and Cardiac Computed Tomographic Data Sets, *J Am Soc Echocardiogr*, vol. 33(11), pp. 1306–1315, 2020.

[63] Noorali A., Hussain Merchant A., Babar Chauhan S., Khan MA.; Ehsan A., Pervez M., Tariq M., Fatimi S.: Conceptual framework for a cardiac surgery simulation laboratory and competency-based curriculum in Pakistan - a short innovation report, *J Pak Med Assoc*, vol. 72(Suppl 1), pp. S103–S105, 2022.

[64] Ojala S ., Sirola J., Nykopp T., Kroger H., Nuutinen H.: The impact of teacher's presence on learning basic surgical tasks with virtual reality headset among medical students, *Med Educ Online*, vol. 27(1), p. 2050345, 2022.

[65] Ong C., Krishnan A ., Huang C., Spevak P., Vricella L., Hibino N., Garcia J., Gaur L.: Role of virtual reality in congenital heart disease, *Congenit Heart Dis*, vol. 13(3), pp. 357–361, 2018.

[66] Pelletier M., Kaneko T., Peterson M., Thourani V.: From sutures to wires: The evolving necessities of cardiac surgery training, *J Thorac Cardiovasc Surg*, vol. 154(3), pp. 990–993, 2017.

[67] Perens G., Chyu J., McHenry K., Yoshida T., Finn J.: Three-Dimensional Congenital Heart Models Created With Free Software and a Desktop Printer: Assessment of Accuracy, Technical Aspects, and Clinical Use, *World J Pediatr Congenit Heart Surg*, vol. 11(6), pp. 797–801, 2020.

[68] Peters T.M., Linte C.A., Moore J., Bainbridge D., Jones D.L., Guiraudon G.M.: Towards a medical virtual reality environment for minimally invasive cardiac surgery. In: *Medical Imaging and Augmented Reality: 4th International Workshop Tokyo, Japan, August 1-2, 2008 Proceedings 4*, pp. 1–11, Springer, 2008.

[69] Proffitt R., Lange B.: Considerations in the efficacy and effectiveness of virtual reality interventions for stroke rehabilitation: moving the field forward, *Physical Therapy*, vol. 95(3), pp. 441–8, 2013.

[70] Rad A., Vardanyan R., Lopuszko A., Alt C., Stoffels I., Schmack B., Ruhparwar A., Zhigalov K., Zubarevich A., Weymann A.: Virtual and Augmented Reality in Cardiac Surgery, *Braz J Cardiovasc Surg*, vol. 37(1), pp. 123–127, 2022.

[71] Raimondi F., Vida V., Godard C., Bertelli F., Reffo E., Boddaert N., El Beheiry M., Masson J.: Tast-track virtual reality for cardiac imaging in congenital heart disease, *J Card Surg*, vol. 36(7), pp. 2598–2602, 2021.

[72] Ralston B.H., Willett R.C., Namperumal S., Brown N.M., Walsh H., Muñoz R.A., Del Castillo S., Chang T.P., Yurasek G.K., Del Castillo S., *et al.*: Use of virtual reality for pediatric cardiac critical care simulation, *Cureus*, vol. 13(6), 2021.

[73] Ramphal P.S., Coore D.N., Craven M.P., Forbes N.F., Newman S.M., Coye A.A., Little S.G., Silvera B.C.: A high fidelity tissue-based cardiac surgical simulator, *European journal of cardio-thoracic surgery*, vol. 27(5), pp. 910–916, 2005.

[74] Reardon M.: Change is the only constant, *J Thorac Cardiovasc Surg*, vol. 154(3), pp. 996–997, 2017.

[75] Reinhard Friedl M.: Virtual reality and 3D visualizations in heart surgery education. In: *The Heart surgery forum*, vol. 2001, p. 03054, 2002.

[76] Sadeghi A., Mathari S., Abjigitova D., Maat A., Taverne Y., Bogers A., Mahtab E.: Current and Future Applications of Virtual, Augmented, and Mixed Reality in Cardiothoracic Surgery, *Ann Thorac Surg*, vol. 113(2), pp. 681–691, 2022.

[77] Sadeghi A., Peek J., Max S., Smit L., Martina B., Rosalia R., Bakhuis W., Bogers A., Mahtab E.: Virtual Reality Simulation Training for Cardiopulmonary Resuscitation After Cardiac Surgery: Face and Content Validity Study, *JMIR Serious Games*, vol. 10(1), p. e30456, 2010.

[78] Sanders J., Bowden T., Woolfe-Loftus N., Sekhon M., Aitken L.M.: Predictors of health-related quality of life after cardiac surgery: a systematic review, *Health and Quality of Life Outcomes*, vol. 20(1), pp. 1–12, 2022.

[79] Sharma R., Singh D., Gaur P., Joshi D.: Intelligent automated drug administration and therapy: Future of healthcare, *Drug Delivery and Translational Research*, pp. 1–25, 2021.

[80] Sibilitz K., Berg S., Rasmussen T., Risom S., Thygesen L., Tang L., Hansen T., Johansen P., Gluud C., Lindschou J., Schmid J., Hassager C., Køber L., Taylor R., Zwisler A.: Cardiac rehabilitation increases physical capacity but not mental health after heart valve surgery: a randomised clinical trial, *Heart*, vol. 102(24), pp. 1995–2003, 2016.

[81] Silva J.N., Southworth M., Raptis C., Silva J.: Emerging applications of virtual reality in cardiovascular medicine, *JACC: Basic to Translational Science*, vol. 3(3), pp. 420–430, 2018.

[82] Skalidis I., Muller O., Fournier S.: CardioVerse: The cardiovascular medicine in the era of Metaverse, *Trends in Cardiovascular Medicine*, 2022.

[83] Szpala S., Wierzbicki M., Guiraudon G., Peters T.: Real-time fusion of endoscopic views with dynamic 3-D cardiac images: a phantom study, *IEEE Trans Med Imaging*, vol. 24(9), pp. 1207–15, 2005.

[84] Talbot H., Spadoni F., Duriez C., Sermesant M., O'Neill M., JaÛs P., Cotin S., Delingette H.: Interactive training system for interventional electrocardiology procedures, *Med Image Anal*, vol. 35, pp. 225–237, 2017.

[85] Theingi S., Leopold I., Ola T., Cohen G.S., Maresky H.S.: Virtual reality as a non-pharmacological adjunct to reduce the use of analgesics in hospitals, *Journal of Cognitive Enhancement*, vol. 6(1), pp. 108–113, 2022.

[86] Valdis M., Chu M., Schlachta C., Kiaii B.: Validation of a Novel Virtual Reality Training Curriculum for Robotic Cardiac Surgery: A Randomized Trial, *Innovations*, vol. 10(6), pp. 383–8, 2015.

[87] Valdis M., Chu M., Schlachta C., Kiaii B.: Evaluation of robotic cardiac surgery simulation training: A randomized controlled trial, *J Thorac Cardiovasc Surg*, vol. 151(6), pp. 1498–1505.e2, 2016.

[88] Venkatesan M., Mohan H., Ryan J.R., Schürch C.M., Nolan G.P., Frakes D.H., Coskun A.F.: Virtual and augmented reality for biomedical applications, *Cell reports medicine*, vol. 2(7), p. 100348, 2021.

[89] Vervoort D., Fiedler A.: Virtual reality, e-learning, and global cardiac surgical capacity-building, *J Card Surg*, vol. 36(6), pp. 1835–1837, 2021.

[90] Vigil C., Lasso A., Ghosh R., Pinter C., Cianciulli A., Nam H., Abid A., Herz C., Mascio C., Chen J., Fuller S., Whitehead K., Jolley M.: Modeling Tool for Rapid Virtual Planning of the Intracardiac Baffle in Double-Outlet Right Ventricle, *Ann Thorac Surg*, vol. 111(6), pp. 2078–2083, 2021.

[91] Villanueva C., Xiong J., Rajput S.: Simulation-based surgical education in cardiothoracic training, *ANZ J Surg*, vol. 90(6), pp. 978–983, 2020.

[92] Vinck E.E., Smood B., Barros L., Palmen M.: Robotic cardiac surgery training during residency: Preparing residents for the inevitable future, *Laparoscopic, Endoscopic and Robotic Surgery*, 2022.

[93] Wang C., Zhang L., Qin T., Xi Z., Sun L., Wu H., Li D.: 3D printing in adult cardiovascular surgery and interventions: a systematic review, *Journal of Thoracic Disease*, vol. 12(6), p. 3227, 2020.

[94] Wang L., Liu J., Xie W., Chen Q., Cao H.: Condition notification assisted by virtual reality technology reduces the anxiety levels of parents of children with simple CHD: a prospective randomised controlled study, *Cardiol Young*, vol. doi: 10.1017/S104795112100500X, 2022.

[95] Watanabe G., Ishikawa N.: da Vinci surgical system, *Kyobu Geka*, vol. 67(8), pp. 686–9, 2014.

[96] Wierzbicki M., Drangova M ., Guiraudon G., Peters T.: Validation of dynamic heart models obtained using non-linear registration for virtual reality training, planning, and guidance of minimally invasive cardiac surgeries, *Med Image Anal*, vol. 8(3), pp. 387–401, 2004.

[97] Xue H., Sun K., Yu J., Chen B., Chen G., Hong W., Yao L., Wu L.: Three-dimensional echocardiographic virtual endoscopy for the diagnosis of congenital heart disease in children, *Int J Cardiovasc Imaging*, vol. 28(6), pp. 851–9, 2010.

[98] Yamada T., Osako M., Uchimuro T., Yoon R., Morikawa T., Sugimoto M., Suda H., Shimizu H.: Three-Dimensional Printing of Life-Like Models for Simulation and Training of Minimally Invasive Cardiac Surgery, *Innovations*, vol. 12(6), pp. 459–465, 2017.

[99] Yeh L.R., Chen W.C., Chan H.Y., Lu N.H., Wang C.Y., Twan W.H., Du W.C., Huang Y.H., Hsu S.Y., Chen T.B.: Integrating ECG monitoring and classification via IoT and deep neural networks, *Biosensors*, vol. 11(6), p. 188, 2021.

[100] Yoo S., Hussein N., Peel B., Coles J., van Arsdell G., Honjo O., Haller C., Lam C., Seed M., Barron D.: 3D Modeling and Printing in Congenital Heart Surgery: Entering the Stage of Maturation, *Front Pediatr*, vol. 9, p. 621672, 2021.

[101] Zanatta F., Farhane-Medina N.Z., Adorni R., Steca P., Giardini A., D'Addario M., Pierobon A.: Combining robot-assisted therapy with virtual reality or using it alone? A systematic review on health-related quality of life in neurological patients, *Health and Quality of Life Outcomes*, vol. 21(1), p. 18, 2023.

[102] Zell E., Dyck E., Kohsik A ., Grewe P., Flentge D., Winter Y.e.a.: A virtual reality system for clinical studies and rehabilitation, *Eurographics Girone, Spain: Eurographics Medical Prize Papers*, pp. 9–12, 2013.

Affiliations

Dariusz Mikolajewski
Kazimierz Wielki University in Bydgoszcz, Institute of Computer Science, Kopernika 1, 85-074 Bydgoszcz, Poland,
Medical University in Lublin, Neuropsychological Research Unit, 2nd Clinic of the Psychiatry and Psychiatric Rehabilitation, Gluska 1, 20-439 Lublin, Poland, darek.mikolajewski@wp.pl

Anna Bryniarska
Opole University of Technology, Faculty of Electrical Engineering, Automatic Control and Informatics, Proszkowska 76, 45-758 Opole, Poland, a.bryniarska@po.edu.pl

Piotr Michal Wilczek
The President Stanislaw Wojciechowski Calisia University, Faculty of Health Sciences, Nowy Swiat 4, 62-800 Kalisz, Poland,
Prof. Zbigniew Religa Foundation for Cardiac Surgery Development, Wolnosci 345a, 41-800, Zabrze, Poland,
Medical Algorithms Sp. z o. o., Aleja Legionow 4, 41-902 Bytom, Poland, p.wilczek@medicalalgorithms.eu

Maria Myslicka
Wroclaw Medical University, Faculty of Medicine, J. Mikulicza-Radeckiego 5, 50-345 Wroclaw, Poland, mariamyslicka38@gmail.com

Adam Sudol
University of Opole, Faculty of Natural Sciences and Technology, Kardynala Kominka 6, 6a, 45-032 Opole, Poland, dasiek@dasiek.info

Dominik Tenczynski
University of Opole, Institute of Medical Sciences, Oleska 48, 45-052 Opole, Poland, esten2000@gmail.com

Michal Kostro
University of Opole, Institute of Medical Sciences, Oleska 48, 45-052 Opole, Poland, michalkostro01@gmail.com

Dominika Rekawek
University of Opole, Institute of Medical Sciences, Oleska 48, 45-052 Opole, Poland, dominikarr01@gmail.com

Rafal Tichy
University of Opole, Institute of Medical Sciences, Oleska 48, 45-052 Opole, Poland, noweczechlo@gmail.com

Rafal Gasz
Opole University of Technology, Faculty of Electrical Engineering, Automatic Control and Informatics, Proszkowska 76, 45-758 Opole, Poland, r.gasz@po.edu.pl

Mariusz Pelc
University of Opole, Institute of Computer Science, Oleska 48, 45-052 Opole, Poland,

University of Greenwich, School of Computing and Mathematical Sciences, Old Royal Naval College, Park Row, SE10 9LS London, UK, m.pelc@gre.ac.uk

Jaroslaw Zygarlicki
Opole University of Technology, Faculty of Electrical Engineering, Automatic Control and Informatics, Proszkowska 76, 45-758 Opole, Poland, j.zygarlicki@po.edu.pl

Michal Koziol
Opole University of Technology, Faculty of Electrical Engineering, Automatic Control and Informatics, Proszkowska 76, 45-758 Opole, Poland, m.koziol@po.edu.pl

Radek Martinek
VSB-Technical University Ostrava, Department of Cybernetics and Biomedical Engineering – FEECS, 17. listopadu 2172/15, 708 00 Ostrava–Poruba, Czech Republic,
Opole University of Technology, Faculty of Electrical Engineering, Automatic Control and Informatics, Proszkowska 76, 45-758 Opole, Poland, radek.martinek@vsb.cz

Radana Kahankova Vilimkova
VSB-Technical University Ostrava, Department of Cybernetics and Biomedical Engineering – FEECS, 17. listopadu 2172/15, 708 00 Ostrava–Poruba, Czech Republic,
Opole University of Technology, Faculty of Electrical Engineering, Automatic Control and Informatics, Proszkowska 76, 45-758 Opole, Poland, radana.vilimkova.kahankova@vsb.cz

Dominik Vilimek
VSB-Technical University Ostrava, Department of Cybernetics and Biomedical Engineering – FEECS, 17. listopadu 2172/15, 708 00 Ostrava–Poruba, Czech Republic,
dominik.vilimek@vsb.cz

Aleksandra Kawala-Sterniuk
Opole University of Technology, Faculty of Electrical Engineering, Automatic Control and Informatics, Proszkowska 76, 45-758 Opole, Poland, kawala84@gmail.com

Received: 21.07.2023
Revised: 29.01.2024
Accepted: 04.02.2024