Current and Future Applications of Virtual, Augmented, and Mixed Reality in Cardiothoracic Surgery

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Background. This review aims to examine the existing literature to address currently used virtual, augmented, and mixed reality modalities in the areas of preoperative surgical planning, intraoperative guidance, and postoperative management in the field of cardiothoracic surgery. In addition this innovative technology provides future perspectives and potential benefits for cardiothoracic surgeons, trainees, and patients.

Methods. A targeted, nonsystematic literature assessment was performed within the Medline and Google Scholar databases to help identify current trends and to provide better understanding of the current state-of-the-art extended reality (XR) modalities in cardiothoracic surgery. Related articles published up to July 2020 were included in the review.

Results. XR is a novel technique gaining increasing application in cardiothoracic surgery. It provides a 3-dimensional and realistic view of structures and environments and offers the user the ability to interact with digital projections of surgical targets. Recent studies showed the validity and benefits of XR applications in cardiothoracic surgery. Examples include XR-guided preoperative planning, intraoperative guidance and navigation, postoperative pain and rehabilitation management, surgical simulation, and patient education.

Conclusions. XR is gaining interest in the field of cardiothoracic surgery. In particular there are promising roles for XR applications in televirtuality, surgical planning, surgical simulation, and perioperative management. However future refinement and research are needed to further implement XR in the aforementioned settings within cardiothoracic surgery.

(Ann Thorac Surg 2022;113:681-91)

Extended reality (XR) refers to all techniques used to generate combined physical reality and virtual 3-dimensional (3D) interfaces that allow human–machine interaction using wearables and remote controllers.[1] This includes the subtechniques virtual reality (VR), augmented reality (AR), and mixed reality (MR). All these interfaces enable the user to either view or interact with computer-generated 3D interfaces in a VR or hybrid (MR and AR) physical and virtual world.[2] With the instantaneous development of new XR devices such as Oculus Rift (Oculus VR, Irvine, CA) and Hololens (Microsoft, Redmond, WA), their potential usability in health care becomes inevitable. It is believed that these emerging digital techniques will have an extensive impact on health care in the upcoming decades, in particular in surgical fields in which narrow and clearcut visualization are a necessity.

XR and its emerging developments have the potential to introduce new opportunities for various applications that may benefit both patients and physicians in the field of cardiothoracic surgery. For instance XR offers the possibility to create interactive interfaces that can facilitate better preoperative planning and enhanced intraoperative navigation and provide patient education and surgical (resident) training. Consequently it is important to explore the potential benefits of XR applications in all these aspects of surgery.

The purpose of this review is to define the concept of XR and its current and potential future impact in the field of cardiothoracic surgery, specifically for surgery on the heart, intrathoracic vessels, and lungs (respectfully excluding upper gastrointestinal surgery). We elaborate on the potential benefits and limitations of XR by reviewing and summarizing currents trends of XR applications in the field of cardiothoracic surgery. Specifically we investigated the application of XR technology for various clinical purposes, including preoperative surgical

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Accepted for publication Nov 8, 2020.

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0003-4975
https://doi.org/10.1016/j.athoracsur.2020.11.030

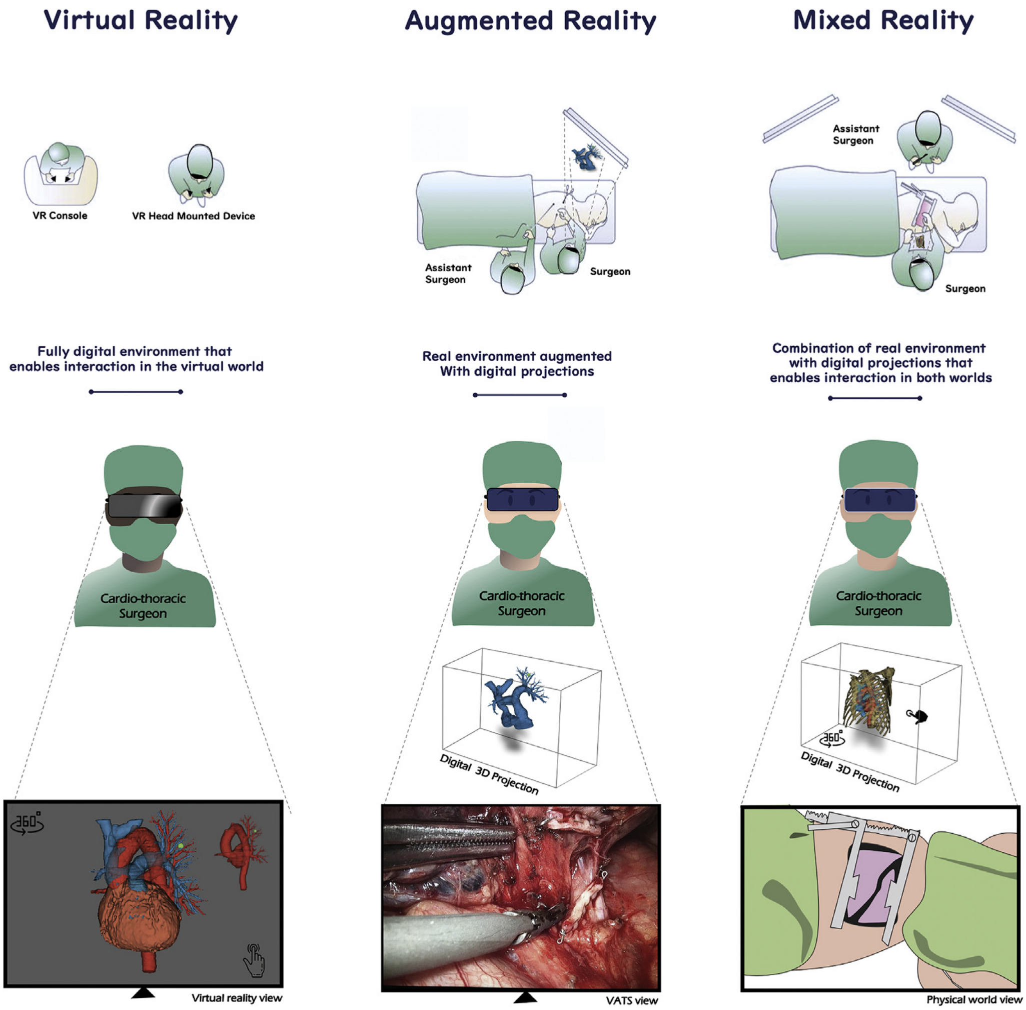

Figure 1. Virtual, augmented, and mixed reality. Clinical and surgical applications of extended reality (XR) modalities in cardiothoracic surgery. Practical examples are displayed for the applicability of XR in preoperative planning (eg, virtual reality [VR], bottom left), guided preoperative planning of lung cancer surgery and intraoperative (eg, mixed [bottom right]) and augmented reality–guided (bottom center) navigation during thoracotomy/VATS for lung cancer surgery. (3D, 3-dimensional; VATS, video-assisted thoracoscopic surgery.)

planning, intraoperative navigation, and postoperative management. Finally in this review we discuss and provide a future perspective on novel and promising XR technologies in the field of cardiothoracic surgery.

Methods

The authors performed a targeted, nonsystematic literature review within the electronic Medline (PubMed) and Google Scholar databases to help identify current trends and provide a better understanding of the current state-of-the-art XR modalities in cardiothoracic surgery. Key search words included but were not limited to VR, AR, and MR; cardiothoracic surgery; preoperative planning; intraoperative navigation; and postoperative management. Furthermore reference lists of all included articles were searched for additional relevant articles. Articles were included if deemed relevant and had content related to the aforementioned key words.

Extended Reality

XR was introduced for the first time in 1986 by computer scientists, as principle of computer-assisted translation of reality to 3D visualization, by using head-mounted devices/displays (HMDs) with at least 1 remote controller serving as a navigation feature.[3] Since then a number of developments have been made in its application in different industries. XR provides the user with the ability to interact in a computer-synthesized environment based on reality. Primarily this technology allows for demonstration of complex objects and simulation of performances in a wide range of clinical applications.

As mentioned above XR consists of 3 subtechniques, VR, AR, and MR (Figure 1). VR is a digital simulated experience based on reality-derived images. Haptic devices, such as controllers with position trackers and motion capture data gloves (HaptX, Seattle, WA), are used to navigate 3D models and at the same time interact with the simulated environment in real time using natural senses and motion (Figure 1, left). AR is the technology that superimposes digital content on the reality we observe. It allows the wearer to see the native environment while placing 2D or 3D images within it (Figure 1, middle). Finally in MR a computer system synchronizes reality and 3D model constructions. This allows surgeons to link the real surgical field view to 3D model constructions of the surgical case, which enables interaction with the surgical

Figure 2. Virtual reality (VR)-guided preoperative surgical planning. An example of preoperative planning of a surgical procedure with VR software (Medical VR, Amsterdam, Netherlands) along with hardware (Oculus VR [Irvine, CA] headset shown here) that allows the display of preoperatively acquired computed tomography in 3 dimensions. In addition VR controllers enable digital manipulation and interaction of anatomic models.

targets in both physical and virtual worlds (Figure 1, right).

Preoperative XR

Even though conventional 2D imaging techniques play an essential role in the diagnostic process and preoperative surgical planning of cardiothoracic surgery, XR modalities could enable 3D, more realistic, and accurate representation of anatomy (Figure 2). Currently the armamentarium of the modern cardiothoracic surgeon consists of different essential imaging modalities such as computed tomography (CT), magnetic resonance imaging (MRI), ultrasonography, and bronchoscopy. However the future cardiothoracic surgeon might also benefit from better and more accurate imaging modalities including 3D CT, virtual bronchoscopy, 4D echocardiography, and XR.

Several benefits of XR for preoperative surgical use have been identified in various studies.[4-6] For example compared with conventional imaging techniques, XR modalities offer the user a 3D and more realistic representation of the surgical target (Figures 2 and 3). In addition they provide better preoperative awareness of rare anatomic abnormalities. Moreover VR- and AR-generated images offer a better (3D) interpretation of anatomic structures, and MR also enables the user to interact, analyze, and edit these virtual anatomic objects without obstructing the normal visual view. Another essential prospect of use is associated with better identification of the relation between different structures inside an organ. For example for the surgical planning of segment resections of the lung XR modalities enable the surgeon to verify whether the tumor is indeed inside the anatomic borders of a particular segment. This can lead to a better preoperative selection of patients who are suitable for segmental anatomic resections. Below and in Table 1 we briefly highlight studies carried out in the context of XR for preoperative surgical planning in congenital, adult cardiac, and thoracic surgery.

Preoperative Surgical Planning: Cardiovascular

Ender and colleagues[4] demonstrated in 2008 that AR technology could benefit mitral valve surgeons in assessing the optimal annuloplasty ring size based on 3D transesophageal echocardiography images of the annulus. In this study the investigators created digital models of a Carpentier-Edwards Physio ring (Edwards Lifesciences, Irvine, CA) that could be superimposed on the transesophageal echocardiography–acquired 3D images of the mitral valve to measure ring size in an XR-enhanced digital environment. In a small study of 9 patients by Chan and colleagues[7] a VR-based imaging technique was compared with conventional CT angiography to prepare for surgical correction of a congenital cardiovascular anomaly, pulmonary atresia with major aortopulmonary collateral arteries. Outcomes were measured in terms of sensitivity, specificity, accuracy, and time to interpret the exact location of these collateral arteries. Sensitivity, specificity, and accuracy were found to be comparable for both methods; however a significant

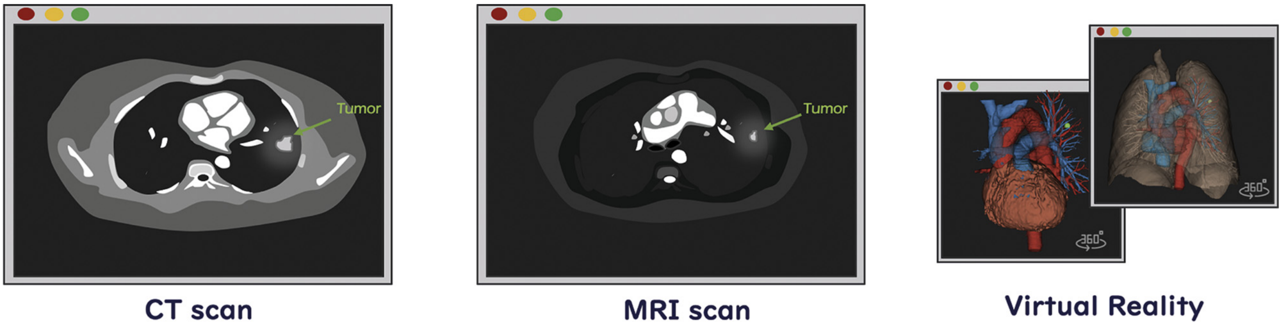

Figure 3. The difference between computed tomography (CT), magnetic resonance imaging (MRI), and virtual reality in preoperative planning. Preoperative CT, MRI, and virtual reality–guided interpretation of anatomic information in a patient with a left-sided pulmonary tumor. The green arrow represents the tumor in CT (left) and MRI (center), and the green nodule represents the tumor in virtual reality (right).

Table 1. Overview of XR-related Studies in the Field of Cardiothoracic Surgery

Area	Topic	Cardiovascular	Thoracic (Pulmonary/ Oncology)	Study Type	Sample Size	XR Modality	Reference
Preoperative planning	Mitral valve annuloplasty ring sizing	✓		Observational (prospective)	50	VR/AR	Ender et al 2008[4]
	Evaluation of major aortopulmonary collateral arteries	✓		Feasibility study	9	VR	Chan et al 2013[7]
	Minimally invasive coronary artery bypass grafting	✓		Case report	1	VR	Sadeghi et al 2020[8]
	Congenital heart surgery	✓		Observational (prospective)	25	VR	Lu et al 2020[9]
	Congenital heart surgery	✓		Observational (retrospective)	7	VR	Haw et al 2019[10]
	Double-outlet right ventricle anatomy review	✓		Observational (retrospective)	20	VR	Farooqi et al 2016[5]
	Ventricular septal defect evaluation	✓		Case report	1	VR	Mendez et al 2019[11]
	Congenital heart surgery	✓		Observational (retrospective)	42	VR	Sorenson et al 2008[12]
	Congenital heart surgery	✓		Preliminary study	1	MR	Brun et al 2019[13]
	Congenital heart surgery	✓		Preliminary study	2	VR	Ong et al 2018[14]
	Thoracoscopic resection of lung cancer		✓	Case report	1	VR/MR/ AR	Frajhof et al 2018[6]
	Lung nodule visualization		✓	Preliminary study	3	MR	Perkins et al 2020[15]
Intraoperative guidance	Echocardiography visualization during mitral commissurotomy	✓		Case report	1	MR	Kasprzak et al 2020[16]
	Valve-in-valve implantation planning	✓		Feasibility study	9	VR/MR/ AR	Belhaj et al 2016[17]
	Congenital heart disease	✓		Feasibility study	8	VR/MR	Bruckheimer et al 2016[18]
	Pacemaker implantation in complex congenital heart disease	✓		Case report	1	AR	Opolski et al 2018[19]
	Lung nodule visualization for intraoperative identification		✓	Feasibility study	8	AR	Rouze et al 2016[20]
Postoperative management	Postthoracotomy rehabilitation		✓	Feasibility study	7	VR	Hoffman et al 2014[22]
	Postoperative rehabilitation	✓		Randomized clinical trial	60	VR	Cacau et al 2013[23]
	Postoperative pain management	✓		Observational (prospective)	67	VR	Mosso et al 2014[24]

AR, augmented reality; MR, mixed reality; VR, virtual reality; XR, extended reality.

improvement in interpretation time was seen (13 minutes vs 22 minutes, $P < .05$) in favor of 3D visualization with VR imaging. More recently our group published a report on the application of immersive VR technology to plan for minimally invasive coronary artery bypass surgery.[8] VR was used to review coronary artery anatomy in a patient with Kawasaki disease. Moreover VR-based reconstructions were used to guide thoracoscopic port placement and anterior minithoracotomy. This report showed the potential utility of XR to guide planning of thoracoscopic port placement for minimally invasive cardiac and thoracic procedures.

In another study by Lu and coworkers,[9] VR 3D modeling was used to evaluate the application of VR technology in the preoperative planning of congenital heart surgery. In this prospective, single-center study 25 patients undergoing repair of a congenital heart defect were selected, and preoperative evaluation was performed using 3 software platforms, QLab (Philips, Amsterdam, The Netherlands), cvi42 (Circle

Cardiovascular Imaging, Calgary, Canada), and True 3D (EchoPixel, Santa Clara, CA), for different imaging modalities including echocardiography, CT/MRI, and VR. The results showed that in most cases the surgeon's preferred choice for preoperative planning was the True 3D (VR) software platform. Furthermore according to most surgeons (>80%) VR-guided preparation resulted in additional information and also led to an alternation of the surgical plan in 2 cases (8%). Another comparable study by Haw and colleagues[10] demonstrated that surgical planning by 3D printing and 3D (VR-based) visualization may enhance understanding in complex (intra) cardiac anatomy and hereby result in better preoperative assessment and planning. This study concluded that preoperative 3D visualization of the anatomy in complex congenital heart surgery can influence decision-making and result in an alteration of repair strategies, thus leading to better outcomes.

Three-dimensional VR models for preoperative congenital cardiac surgery planning were also created by 3 other groups to study and present the benefit of 3D virtual surgery planning in patients with congenital cardiac defects, including double-outlet right ventricle, ventricular septal defects, tetralogy of fallot, and hypoplastic left heart syndrome. Here postprocessing images of cardiac MRI were used to identify structures and spatial arrangement of anatomic parts of the cardiovascular system such as ventricular septal defects, ventricular cavity size, and the great arteries.[5,11,12] Mendez and colleagues[11] and Sorenson and associates[12] demonstrated a precise correlation between the preoperatively acquired VR simulation and the surgeon's view intraoperatively during ventricular septal defect closure. This indicates the additional value of VR-based 3D planning of congenital heart surgery.

In the context of double-outlet right ventricle another recent study assessed the feasibility of XR holograms for creating patient-specific 3D MR models.[13] CT angiography images of a pediatric patient with double-outlet right ventricle and transposition of the great arteries were used to construct a 3D holographic MR model of the heart that could be reviewed by using an HMD (Microsoft Hololens). The authors concluded that this XR modality provided a good diagnostic value and might play a relevant role as a preoperative planning tool, especially for interpretation of congenital heart disease morphology. Finally, regarding VR applications in congenital cardiac surgery, Ong and colleagues[14] studied the feasibility of VR for surgical repair of complex congenital heart disease in 2 infants. An HMD (HTC Vive; HTC, New Taipei City, Taiwan) was used to create 3D VR simulation of cardiovascular defects (eg, ventricular septal defect, truncus arteriosus, and aortic arch hypoplasia).[14] In this study CT angiography–acquired images were used and 3D segmentation was performed by using specialized software (3D Systems, Rock Hill, SC). The authors concluded that 3D visualization (compared with 3D echocardiography, CT, and MRI) in VR comes with the advantages of increased realism, depth perception, and the possibility to display the anatomy from a surgeon's view. An important disadvantage, however, is the lack of standardized software that enables fully automatic image processing for accurate segmentation without manual effort.

In the light of these promising applications of XR in preoperative surgical planning, caution must remain in the broad implementation of these techniques in clinical practice. Larger multicentral, prospective, observational studies are needed to ensure the safety and efficacy of these techniques as well as their assessment on patient outcomes.

Preoperative Surgical Planning: Thoracic

To date only a few studies are available on the use of XR technology for preoperative planning in the setting of oncologic lung surgery. Frajhof and associates[6] published a case report on the application of AR, MR, and VR tools in the preparation and intraoperative guidance of a video-assisted thoracoscopic lobectomy. Perkins and colleagues[15] also reported on the development of a new software that runs on the Microsoft Hololens HMD for MR visualization of CT images for preoperative use. The techniques described allow surgeons to translate conventional 2D CT to an MR model for detailed exploration and manipulation of the surgical target, specifically for localization of small lung nodules and optimization of the desired surgical approach for resection of malignant tissue. Because the software allows full interaction with the MR model of the surgical target and the surrounding organs, it provides great advantages in preoperative surgical planning. The benefits have been studied retrospectively in 3 patients who underwent wedge resection for lung nodules.[15] This MR tool provided a more precise localization of the lung nodules, more accurate determination of resection margins, and better estimation of localization alterations of the nodules (due to deformation of surrounding structures such as lung deflation). Additionally this MR platform enabled simulation of surgical instrument placement. This is also another example of how XR technology could assist in guiding thoracoscopic port placement. This new tool seems to be promising for future implementation in thoracic surgical planning. However further development and additional clinical research are necessary to prove its utility.

Intraoperative XR Guidance

Most of the currently developed medical devices using XR technology–based visualization are aimed at preoperative application; however major potential advantages can also be gained during intraoperative use of these modalities. Because XR technology allows the user to overlay preoperatively constructed 3D models onto the real surgical field, it can provide detailed anatomic (and physiologic) information and intraoperative guidance to ease and support a procedure and make its performance more accurate, safe, and efficient (Figure 1). The ultimate goal of intraoperative implementation of XR technology in the field of cardiothoracic surgery must benefit the surgeon and patient and improve quality of care and

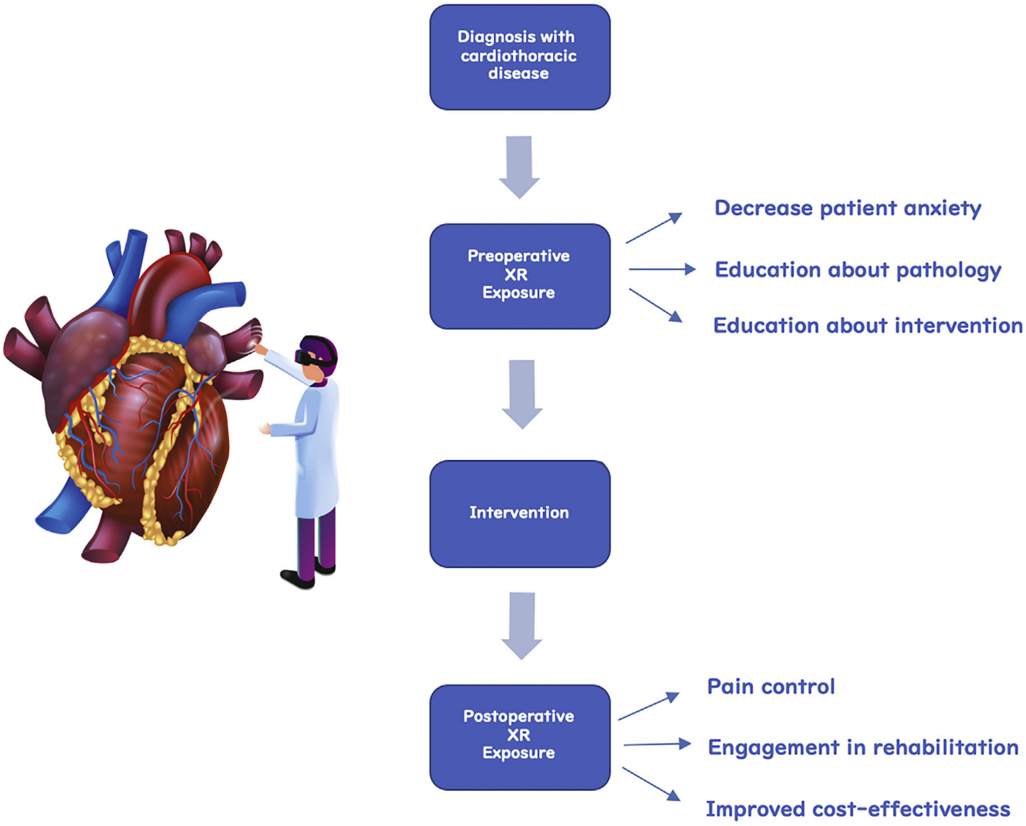

Figure 4. Flowchart for care optimization using extended reality (XR).

health outcomes. Moreover by creating virtual projections of anatomic structures a surgeon's lack of tactile feedback (such as in robotic and minimally invasive video-assisted surgery) can be partially compensated for by visual augmentation during an operation.

Intraoperative Guidance: Cardiovascular

A recent case report in the field of interventional cardiology by Kasprzak and coworkers[16] described the periprocedural use of MR guidance for performing balloon mitral commissurotomy. The authors reported the development of a model that allows real-time streaming of 3D reconstructed transesophageal echocardiography images to an HMD showing a hologram of the surgical target as an overprojection on the real (physical) view of the operator. This MR tool allows the operator to control the hologram by voice commands and hand gestures perceived by the HMD. Regarding percutaneous treatment of structural heart disease, XR has also demonstrated a benefit to interventionalists as an intraoperative guiding tool for transcatheter heart valve implantation/repair and atrial septal defect closure. Belhaj Soulami and colleagues[17] demonstrated that computer-assisted virtual reconstructions of vascular anatomy (eg, aortic root) could be used to create augmented fluoroscopy images during valve-in-valve transcatheter aortic valve implantation.

Finally regarding intraoperative navigational XR tools Bruckheimer and associates[18] reported on the application of 3D holograms (without using HMDs) to guide percutaneous transcatheter atrial septal defect closure and pulmonary valve implantation. Also a case report was published to demonstrate that AR could help to guide a challenging transvenous approach for pacemaker implantation in a patient with congenitally corrected transposition of great arteries and dextrocardia.[19]

Intraoperative Guidance: Thoracic

A study by Rouze and coworkers[20] described an intraoperative guidance technique using cone-beam CT for small pulmonary nodule localization to direct lung resection during video-assisted thoracoscopic surgery with augmented fluoroscopy overprojecting the real-time surgical field. A preprocedural 3D reconstruction of the lung nodules was performed in 8 patients based on cone-beam CT images, which were converted into augmented fluoroscopic images overprojecting the video-assisted thoracic procedure to guide the surgeon in locating the targeted nodules. All nodules were localized and resected successfully. This initial study emphasizes the feasibility of the intraoperative use of XR to improve the accuracy and surgical outcomes in cardiothoracic surgery. Another interesting application of real-time augmentation of the surgical field is the application of AR to visually guide the detection of lymph nodes or small intrathoracic nodules.

In the context of thoracic oncology some literature is available on the augmentation of the surgical view by using indocyanine-green fluorescence imaging for lymph node detection.[21] Specifically this could be interesting in intraoperative identification of sentinel nodes in patients with lung cancer undergoing segmentectomy. Hopefully this type of research will pave the way for future developments of AR-based imaging systems that enable identification of lymph nodes by projecting preoperatively acquired imaging data (eg, positron emission tomography) onto the real surgical field. This could potentially eliminate the need for fluorescence imaging and provide easy thoracic lymph node detection and dissection.

XR in Postoperative Management

In addition to intraoperative navigation and preoperative planning, XR modalities can also be implemented in other postoperative settings. For example they could provide the ability to immerse a patient in a VR as a (distraction) method during stressful, painful, or rehabilitative situations. A few clinical applications of XR techniques have been described in the setting of postoperative care after cardiothoracic procedures. Hoffman and colleagues[22] investigated the use of a VR-based approach to perform home-based exercises after a thoracotomy for lung cancer. The authors explored the feasibility of a VR-based intervention (the promotion of regular and light-intensity walking and balance exercises carried out on a VR game console) to promote postoperative rehabilitation support to address fatigue after thoracotomy for non-small cell lung cancer resection. The authors concluded that a self-managed and VR-based in-home (after discharge) intervention might be potentially effective for addressing cancer-related fatigue after hospitalization for thoracotomy. However it was acknowledged that because this was a feasibility study (based on a small patient group [$n = 7$]) a larger randomized clinical trial is needed for further evaluation. In a study by Cacau and colleagues[23] a VR interface was used successfully as an adjunct to already existing post–cardiac surgery rehabilitation protocols. In this study a small group ($n = 60$) of postcardiac surgery (elective coronary artery bypass grafting and/or valve replacement) patients were randomized into a conventional physical therapy group and a VR-assisted physical therapy group. In both groups patients performed (twice daily) physiotherapy exercises such as breathing, airway clearing, metabolic, and motor exercises. Specifically the treatment group differed from the control group in that it performed the motor exercises using VR. Study results showed a beneficial outcome for the VR-treated group (when compared with conventional physical therapy) in terms of several rehabilitation factors, including less postoperative pain, better functional performance, better walking capacity, and higher energy levels. Additionally VR as an adjunct to conventional physiotherapy showed faster recovery of patients and shorter length of hospital stay. The authors concluded that VR-assisted physiotherapy seemed to be an effective method to stimulate postoperative recovery of patients after cardiac surgery.

Important factors that greatly influence postoperative recovery and rehabilitation after cardiothoracic procedures are psychological stress and postoperative pain.[24] In different fields of medicine VR therapy has shown its efficacy and popularity in managing postoperative pain. VR modalities for the management of postoperative anxiety and pain have also been explored in cardiac surgery patients. Mosso and coworkers[24] hypothesized that the use of VR cybertherapy could reduce postoperative pain and promote overall well-being of patients after cardiac surgery by enabling relaxation and (pain) distraction in an intensive care unit. By applying so-called VR distraction therapy the researchers aimed to distract the patients' ($n = 67$) attention to a VR instead of pain. Their results showed that a significant number of patients (88%) experienced less pain after VR therapy. Moreover it was demonstrated that physiologic changes, such as decreased heart rate, respiratory rate, and arterial blood pressure, took place after only 30 minutes of VR therapy.

In conclusion it can be stated that over the past few years there has been a growing interest in and popularity of VR-based approaches to improve postoperative recovery after cardiothoracic surgery. In the next few years a larger body of evidence will be needed to draw better and more evidence-based conclusions on the effects of XR in the postoperative setting.

Future Perspectives

Advances in the hardware and software industry of XR have driven the development of more advanced technologies that are suitable for medical and surgical applications. Although XR applications have not been used widely in cardiothoracic surgery, they have already shown great potential to provide (future) cardiothoracic surgeons with tools that enable improved diagnostics, preoperative planning, intraoperative guidance, and postoperative treatment. Without doubt more refinement is required to develop further suitable applications and to confirm favorable outcomes in the use of these techniques in cardiothoracic surgery. However considering the speed of progress and development of XR in other fields it is expected that in the near future XR will make its way into the operating theaters and wards of cardiothoracic surgery.

Immersive Televirtuality

In addition to its use as a 3D imaging tool XR could serve as a communication tool in modern clinical medicine. For example it was demonstrated that by using Microsoft Hololens and MR Thrive software (Aetho, San Francisco, CA) it was possible to organize a remote meeting between surgeons as 3D digital avatars in the same virtual environment.[25] One could imagine that this type of immersive technology could facilitate multidisciplinary team meetings with surgeons and other healthcare providers from all over the world and regional referring hospitals.[26] Accelerated by the coronavirus disease 2019 pandemic our research group is currently exploring these possibilities in ongoing studies.

Another futuristic method of intraoperative guidance could be the use of MR toward remote virtual–physical assistance. For instance surgeons in the learning curve in other areas of the world could get telementoring from experienced surgeons in remote locations through an MR experience. In addition telepresence surgery, which is the ability to perform robot-guided surgery remotely with the aid of XR technology, could become a reality in the field of cardiothoracic surgery.[27] Moreover by merging XR and robotic technology a surgeon's lack of tactile feedback in robotic surgery might be partially balanced by visual sensation during an operation.

Virtual Guidance of Pulmonary Resections

Because the heart and lungs are dynamic and deformable surgical targets, intraoperative imaging guidance can be quite challenging. A possible solution to this challenge is the use of the combination of navigational bronchoscopy and imaging techniques in a hybrid operating theatre. In the past few years there has been a significant increase in the number of pulmonary sublobar anatomic resections due to better diagnostic imaging modalities, such as multislice CT. Moreover the recently published NELSON trial demonstrated a potential survival benefit for high-risk people undergoing screening to detect lung cancer in an early stage of the disease.[28] Consequently there might be a considerable increase in the number of segmental anatomic pulmonary resections in the next decades. Intraoperative palpation of small lung cancer nodules might be very challenging, especially when minimally invasive approaches, such as robotic and video-assisted thoracic surgery, are performed. Navigational bronchoscopy is a novel bronchoscopy technique based on preoperative CTs that enables an accurate and easier localization of small peripheral nodules in the lung parenchyma.[29] By merging virtual bronchoscopy images with navigational bronchoscopy techniques, sublobar anatomic resection could potentially be performed with higher accuracy, safety, and efficiency.

Another interesting tool is virtual bronchoscopy. It has been applied as a diagnostic tool in reviewing masses and stenosis of the airways but not in the preoperative setting.[30] Future applications of this imaging technique might offer better insights in preparing (trachea-) bronchial sleeve resections for centrally located tumors that might not allow easy passage of a standard flexible bronchoscope. Additionally in the context of preoperative planning several reports have already proven some of the benefits that 3D imaging (eg, 3D CT) could offer in pulmonary resections.[31,32] Based on some of these results it has been suggested that 3D modeling of CTs could contribute to better identification of anatomic abnormalities, recognition of suitable cases for pulmonary segment resections, and improved estimations of resection margins.[33] Consequently it is expected that with the recent advances in 3D CT and XR technology the very first 3D XR-guided planning and intraoperative guidance of an anatomic pulmonary resection could be performed in the near future. An essential aspect that would encourage the use of these modern technologies in the cardiothoracic surgical community is an open-minded, receptive attitude of surgeons toward these new digital interfaces.

Perioperative Management and Patient Education

Another valuable benefit that XR could offer in the pre- and postoperative settings is the application of VR in reducing anxiety and stress in patients undergoing major cardiac and lung surgery. Although many studies on this subject have not been published in the field of cardiothoracic surgery yet, the results from other fields of surgery are promising.[34] Furthermore we believe that XR technology will expand its applicability in perioperative care by allowing anesthesiologists and physical therapists to provide innovative interventions to improve sedation, pain management, postoperative rehabilitation, and patient relaxation. Besides novel medical management strategies XR can provide patients with novel interactive information resources to support the healthcare learning process and to educate patients with cardiovascular and thoracic diseases (Figure 4).

Novel Cardiothoracic Surgical Simulators

Various published studies have shown the advantages of implementation of XR applications in cardiothoracic surgery training.[35-37] In general most models have shown great potential for implementation in cardiothoracic surgery training programs. However all developed systems were built using either existing VR surgery simulators in other surgical specialties or self-built systems that were never followed up or made commercially available. This leaves the field of cardiothoracic surgery still in need of an ideal VR surgical training simulator that can be used to train future cardiothoracic surgeons on ex vivo simulated models (Figure 5). Because simulation tools seem to score high in their potential to mimic reality[38] and their possibility to present a varying set of cases and differing levels of difficulty, there is no doubt for clinical usefulness. Apart from visual simulation advantages the development of instrumental simulation tools having haptic feedback also seems to add great value to the potential of surgical training simulators in cardiothoracic surgery. All these aforementioned benefits of VR surgical training simulators are suitable for use by surgical residents during their training stage, for less experienced surgeons attempting to master surgical techniques, and for experienced surgeons learning new surgical procedures.

Furthermore such simulators also allow utilization in medical education in providing better understanding of complex pathologic anatomic constructions in their physiologic context. Such a technique possibly outperforms the conventional 2D education materials used in medical schools. This could contribute to better preparation of medical students for their following surgical residency, which also might result in an overall higher learning curve. One of the few available studies on this

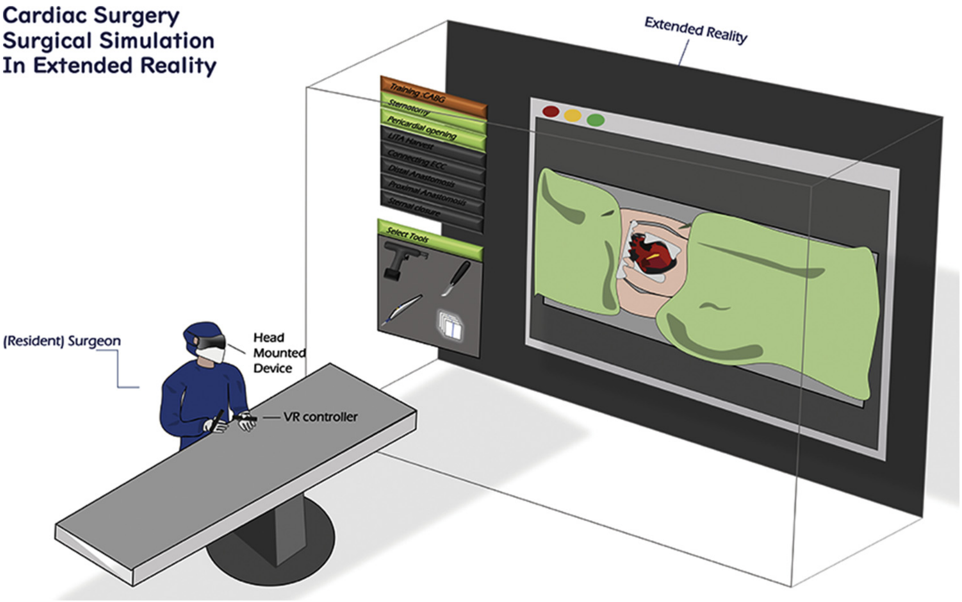

Figure 5. *Cardiac surgery simulation in extended reality. Concept of a cardiac surgical training simulator with the required equipment: a head-mounted device, a VR controller, and an extended reality view based on fitting software. (CABG, coronary artery bypass grafting; ECC, extracorporeal circulation; LITA, left internal mammary artery; VR, virtual reality.)*

topic showed the effectiveness of using 3D anatomic models versus conventional teaching materials, resulting in overall better study grades in a group of 100 medical students.[39] However 3D anatomic education is not yet widely applied, and the literature is limited on the effective usage of this innovating educational platform.[40] Altogether this underlines the need for future studies to confirm the added value of its promising potential also in the field of medical education.

Limitations and Challenges

This review examines the current state-of-the-art applications of XR modalities in the field of cardiothoracic surgery. Even though a thorough and comprehensive literature review was performed, this was not a systematic literature review to evaluate specific topics. The goal of this article was mainly to review current trends and to provide the readers with a broad understanding of current developments in this area of research. Despite the growing interest and increasing trend toward application of XR in surgery, structural implementation of this technology demands more and larger (randomized) clinical trials to evaluate the value of XR for regular and safe use in different clinical and nonclinical settings. Most available studies in this review focus on technical feasibility, effectiveness, usefulness, and operative outcomes (such as operation time) of XR modalities. However to widely adopt XR in cardiothoracic surgery in the future, more comparative studies evaluating clinical endpoints are required. Moreover the economic impact of XR is an important factor in further clinical implementation of this technology. Until now a few studies have been conducted on the cost-effectiveness of XR in other medical domains.[41,42] However to analyze further financial aspects and to investigate whether cardiothoracic surgical applications of XR are cost-effective and cost-saving, future economic analyses are needed. XR technology is still relatively expensive, and the development of novel hardware and software mainly depends on teamwork with people from different disciplines, which makes fast adoption of this technology even more challenging.

As mentioned above we believe that before broad implementation of this technology is brought to clinical practice, larger multicentral, prospective, observational studies are required to ensure the safety and efficacy of these techniques as well as its assessment on patient outcomes. Users will need additional training. Considering the wide range of features the XR can offer, costs will depend on the number of licenses purchased. Potential privacy and security concerns include the risks of breaches involving improperly protected personal information, which should be highlighted, and all preventive measures should be taken by the developers.

Conclusion

Rapid development of novel hardware and software in the field of XR have provided new applications and solutions for a wide range of surgical challenges. Although XR is not yet broadly used in cardiothoracic surgery, it has already shown great potential to improve preoperative planning, intraoperative navigation, patient education, and surgical training. Further research is required to develop the application of these techniques in cardiothoracic surgery. Further advancement of digital systems specified to cardiothoracic surgery will allow more accurate and detailed studies in this still unexplored, promising field. Over time XR modalities need to prove their value by improving surgical and patient outcomes and trainee competence and by reducing surgical complications. We believe that XR technology will expand in the future to provide more realistic, accurate, and relevant applications in the previously discussed areas.

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Extended Reality Platforms: A Technological Solution Still Finding the Right Problem

Invited Commentary:

In this issue of *The Annals of Thoracic Surgery*, Sadeghi and colleagues[1] provide a review of the current state-of-the-art use of extended reality in the field of cardiothoracic surgery. They summarize current applications of virtual, augmented, and mixed reality platforms for cardiothoracic surgery in clinical practice and medical education. The included studies provide early examples of the use of these innovative technologies for preoperative planning, intraoperative guidance, postoperative rehabilitation, patient education, and surgical simulation.

Although there have been significant improvements in the hardware and software of extended reality platforms over the last decade, the current review highlights just how early we are in the adoption of such technology into the field. Almost all studies included in the review are preliminary work consisting predominately of case reports and feasibility studies, with very few studies incorporating clinically relevant endpoints related to patient-centered outcomes. The area that is the furthest towards clinically meaningful adoption is in postoperative rehabilitation, where extended reality platforms have been shown to correlate with less postoperative pain, better functional performance, and decreased psychological stress for patients while recovering from cardiac surgery.[2,3]

The authors also describe potential future applications of extended reality, including immersive televirtual visits and intraoperative consults, as well as improved simulators for surgical training. Particularly during the COVID-19 pandemic, technological solutions that retain high-quality surgical care while maximizing social distancing are certainly needed in both clinical and educational venues.[4] Nevertheless, although the use of these new technologies is exciting and appealing, the focus must remain on how such technology can improve patient outcomes and/or improve hospital or procedural efficiency. As the authors point out, these advances are occurring at an impressive pace, and the innovation will continue to far outpace adoption. Clinicians should remain the gatekeepers for determining how and when such platforms can be adopted to improve the care of our patients and the education of the next generation of surgeons.

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Published by Elsevier Inc.

0003-4975/$36.00
https://doi.org/10.1016/j.athoracsur.2020.11.064