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▶ **To cite this version:**

Fabien Lareyre, Arindam Chaudhuri, Cédric Adam, Marion Carrier, Claude Mialhe, et al.. Applications of Head-Mounted Displays and Smart Glasses in Vascular Surgery. Annals of Vascular Surgery, 2021, pp.497-512. 10.1016/j.avsg.2021.02.033 . hal-03362909

HAL Id: hal-03362909

https://hal.science/hal-03362909

Submitted on 22 Aug 2023

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Version of Record: https://www.sciencedirect.com/science/article/pii/S0890509621002521
Manuscript_bc3658934dabd80923849ebb7bcf5b94

Applications of head-mounted displays and smart glasses in vascular surgery

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Keywords: head-mounted displays; smart glasses; vascular surgery; artificial intelligence; extended reality; virtual reality; augmented reality; mixed reality

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Type of manuscript: Review

Abstract:

Objectives: Advances in virtual, augmented and mixed reality have led to the development of wearable technologies including head mounted displays (HMD) and smart glasses. While there is a growing interest on their potential applications in health, only a few studies have addressed so far their use in vascular surgery. The aim of this review was to summarize the fundamental notions associated with these technologies and to discuss potential applications and current limits for their use in vascular surgery.

Methods: A comprehensive literature review was performed to introduce the fundamental concepts and provide an overview of applications of HMD and smart glasses in surgery.

Results: HMD and smart glasses demonstrated a potential interest for the education of surgeons including anatomical teaching, surgical training, teaching and telementoring. Applications for pre-surgical planning have been developed in general and cardiac surgery and could be transposed for a use in vascular surgery. The use of wearable technologies in the operating room has also been investigated in both general and cardiovascular surgery and demonstrated its potential interest for image-guided surgery and data collection.

Conclusion: Studies performed so far represent a proof of concept of the interest of HMD and smart glasses in vascular surgery for education of surgeons and for surgical practice. Although these technologies exhibited encouraging results for applications in vascular surgery, technical improvements and further clinical research in large series are required before hoping using them in daily clinical practice.

Introduction

Recent advances in virtual reality (VR), augmented reality (AR) and mixed reality (MR) technologies and their democratisation have led them to be readily available at an affordable cost and have widened perspectives in developing applications for clinical practice. Investors aim at developing new tools oriented toward healthcare and various devices are currently being tested. Among them, smart glasses and head-mounted displays (HMD) are wearable technologies especially attractive in surgical settings as they allow the user to access various data and information without the need to handle the device, leaving hands free and preserving environmental sterility.

Examples of such technologies include Google Glass (Google, Mountain View, CA), Meta Glass (Meta Company, San Mateo, CA, USA), HoloLens (Microsoft Corporation, Redmont, WA, USA), Oculus (Oculus VR, Meno Park, CA, USA), Optinvent (Rennes, France), Vuzix (Vuzix, Rochester, NY, USA), or HTC Vive. A variety of potential use of face-mounted computers across surgical settings can be expected within the next few decades. Here, we aim to introduce the fundamental concepts associated with the HMD and smart glasses technology and to discuss potential applications and current limits for their use in vascular surgery.

Fundamental concepts

Head-mounted display (HMD) is a device worn on the head as part of a helmet that has an optical display, allowing the user to project images or see through it.

Smart glasses correspond to a wearable technology that allows to display information in the user's visual field of view (1).

HMD and smart glasses are *wearable technologies*, meaning that they are smart electronic devices that can be worn on the body without interfering with the user's movement (2).

Virtual reality (VR) groups a set of technologies that allow to create an artificial world that does not physically exist and is made to appear by a software (3). This artificial world can mimic and simulate the real world or can be a totally imaginary world. It fully immerses users inside a digital environment that is not necessarily connected to the real world.

Augmented reality (AR) consists in blending virtual objects into the real world. It superimposes digital overlays onto the real world to augment the user's perception of the world (4, 5). Superficial interactions between the virtual objects and the real world are possible but limited.

Mixed reality (MR) corresponds to the merging of real and digital worlds, where digital (virtual) and physical (real) objects co-exist in space and can interact in real time (6, 7). In this system, the digital object is spatially aware and responsive. The user can interact with it and manipulate it.

Extended reality (XR) is a generic term that refers to all combined real and virtual environments that are used to simulate or enhance the physical world. It includes VR, AR and MR.

HMD and smart glasses correspond to a wearable technology that can be implemented with virtual, augmented and mixed reality (Figure 1). Various applications can be developed, and the literature published so far on its use in vascular surgery is scarce. Here, we summarize main applications that have been tested in surgery to provide an overview of the perspectives that could be developed in vascular surgery (Figure 1).

HMD and smart glasses for education and training of surgeons

Use of HMD for anatomical teaching

Technological advances shape medical education and the interest of XR applications are emerging, especially for anatomical teaching and learning (Table 1). A study aimed to explore

whether VR and AR could enhance student learning, engagement and performance. A total of 59 participants were allocated 3 learning modes: VR, AR or tablet-based applications and they underwent an anatomical knowledge assessment after a lesson of skull anatomy (8). While VR and AR offer an alternative to anatomical teaching on cadavers, the methods did not demonstrate a significant difference on the mean assessment score compared to tablet-based application. The users reported increased immersion and engagement with enjoyment in using new technology, but participants using VR experienced more frequently headaches, blurred vision or dizziness. They also highlighted the need of time to get used to the technology during the first utilization. As XR technology tends to be more and more used in daily life, it can be anticipated that they will be progressively incremented in medical and surgical education within the next few decades.

Use of HMD for surgical training

A major application of XR technology for surgical education is the use of simulation to train young surgeons. A single-blind randomized control trial investigated the interest of VR experience with Oculus Rift in surgical education and demonstrated its interest to improve the knowledge and self-confidence of surgical residents (9). In addition, VR simulators offer the possibility to monitor the movements and the behavior of the operators, making it an interesting tool to analyze and assess the surgical psychomotor skills during the procedure (10). Using data collected during the simulation (i.e: behavior, movements, physiological data), artificial intelligence (AI)-derived methods such as machine learning techniques could be proposed to identify patterns predictive of the technical success and provide a feed-back to the user to enhance his surgical skills (11). VR simulators and AI could help to develop multifactorial and objective tools to evaluate the technical competences of surgeons. This

kind of approach could be of interest to fulfill the requirements toward quality assessment, certification and accreditation (12).

Use of HMD for surgical teaching

Other investigators aimed to investigate if smart glasses could potentially improve surgical teaching by allowing the instructor to visualize “blind areas” (13). Intra-operative teaching remains the gold standard to learn surgery, but trainers and instructors are often confronted to barriers due to limited field of view, especially in procedures with limited surgical exposure. The use of the wearable surgical visualization system with Google Glass was tested by 11 surgery residents in a simulated operative field, in which the video was streamed from the leaner to the trainer in real time. The system allowed an efficient simultaneous visualization by the mentor and the resident of the operative field, with an improvement of the mean composite error, without a significant impact on task completion. Most of the users found the device unobtrusive, easy to operate and useful for communication and instruction.

Use of HMD for telementoring

Major advances in communication technology over the past decades have contributed to the raise of telemedicine and allowed patients to access to some medical resources or consulting without the need of being physically present. Surgical training and education is also evolving with the integration of these new technologies and telementoring, which consists of mentoring through telecommunications or computer networks, is now emerging. Liu *et al*. investigated the interest of AR navigation system based on HoloLens for surgical training and telementoring (14). The study was conducted in a lab setting and the system used a stereo camera to track the 3D position of a scalpel and transfer its coordinates wirelessly to the HoloLens device. A scenario of surgical training was tested in which a virtual surgical scene

with pre-recorded surgical annotations was superimposed with the physical surgical scene and the trainee had to operate following the virtual instructions. A scenario for telementoring was also evaluated in which the virtual surgical scene was co-registered with the physical scene and an experienced surgeon guided a virtual scalpel to provide the AR guidance to the inexperienced on-site operator. The performances of the system during the benchtop experiments demonstrated a tracking accuracy less than 2 mm. This raise hopes to use it for surgical education or telementoring, especially in remote areas with limited resources. Experiments in animal models are currently ongoing to address the clinical applicability of the system.

While this pilot study showed potentially encouraging results for the use of HMD for telementoring, disappointing findings were reported for the application of smart glasses in this setting (15). In a single-study institution involving 34 surgeons, 50% rated Google Glass video as fair and 50% as bad to poor for telementoring, mainly due to inadequate image quality.

Potential applications in vascular surgery

While no study has specifically investigated the use of HMD or smart glasses for teaching or training in vascular surgery, a first step would be to use it to train young surgeons in a lab setting with the simulation of vascular and endovascular procedures. Simulators using VR in vascular surgery are currently being developed and a democratization of their use could be expected within the next few years (16, 17). By allowing 3D visualization, HMD could also be applied in an extremely near future to teach vascular anatomy. However, we believe that a large amount of research and technical improvements are required before hoping using wearable technology in daily practice for telementoring in context of vascular surgery.

HMD for pre-surgical planning

Pre-operative planning is a critical step in vascular surgery and imaging plays a key role in analyzing the patient's vessel characteristics. It allows the surgeon to localize the lesions, identify tortuosity or calcifications, measure the diameters and lengths of the vessels, perform the sizing for endografts. Vascular anatomy is complex as vessels exhibit high variability of morphology, size and curvature and three-dimensional (3D) reconstructions are often used to plan the surgical intervention. The desktop environment is traditionally used to visualize 3D reconstructions, but its efficiency can be limited (18). XR technology has brought new insights to improve visualization and pre-surgical planning (Table 2).

Applications in general surgery

A first study compared the usability of 2 commercially available VR applications using the Vive headset (HTC corporation) to visualize computed tomography (CT) scans and accomplish tasks such as selecting an image, a tool, marking a region of interest or using cut planes (19). The user satisfaction was evaluated by 8 surgeons using a think-aloud protocol, semi-structured interviews and a post-study questionnaire. While the overall impression of the users was positive, they reported a general sense of frustration using the application, with gesture-based control being confusing for some users. The applicability of the Oculus Rift to display 3D anatomical model using hand gesture and voice interaction was evaluated in another study involving 10 participants and the users agreed that the system could release the mental burden and help anatomical visualization in complex cases (20). Finally, some investigators aimed to compare three visualization environments for 3D exploration to provide practitioners initial evidence for immersive tangible AR (21). In this study, 15 participants compared 4 visualization tasks using HoloLens, hand-held tablet or traditional desktop environment. Even if the participants found good performance for immersive tangible

AR, the desktop environment offered superior precision, speed and familiarity across most tasks. A slight improvement in performance for the immersive AR environment was observed over several days, highlighting the importance of the training to get used to this technology.

Applications in cardiac surgery

The feasibility to use a MR hologram platform for the diagnosis and operative planning has recently been investigated for cardiac surgery and complex congenital heart diseases (22). In this study, a 3D heart model was segmented from CTA images and the hologram was visualized using HoloLens. The user experience and performance for morphological and diagnostic evaluation was assessed by 36 heart team members. The users rated the platform positively, although they suggested some improvements especially for the hologram manipulation tool.

Potential applications in vascular surgery

The results obtained from the above studies provide encouraging results for a potential use in vascular surgery, with the possibility to develop tools that could help the surgeons to better visualize complex vascular anatomy and plan the intervention. The field is in its infancy and further studies are required to explore this potential application in vascular surgery and with a large number of users.

HMD and smart glasses for image-guided surgery

Applications in general surgery

Image-guided surgery (IGS) corresponds to any surgical intervention where the surgeon uses pre-operative or peri-operative images in order to guide the procedure (23). The use of AR in

IGS could be useful to allow a direct visualization of imaging data on the patient by the surgeon (Table 3). In this aim, some authors developed an AR IGS by integration of the HoloLens to display the IGS planning directly in the working field of the operator (24, 25). Meulstee et al. tested the accuracy of the system on a 3D-printed phantom model and compared with a conventional IGS system. It demonstrated encouraging results to obtain virtual view of the patient's anatomy and the position of the instruments, offering a more intuitive visualization of complex structures. The system does not require the need of the traditional display screen and avoids for the surgeon the loss of direct vision on the surgical field, eliminating the switching focus problem and potentially improving hand-eye coordination and focus. Even if some improvements are needed including calibration to reduce the AR visualization error or implementation of MR reality to interact more intuitively with the virtual images, this technology could help to improve the results of IGS.

The interest of HoloLens has also been investigated in ultrasound guided interventions (26). A randomized cross-over study involving 20 participants was conducted to test the task duration and the accuracy of the AR-HMD to place needles in a training model as compared to standard procedure without visual overlay. The system demonstrated a better accuracy, but the task duration was not reduced. A qualitative study was then performed with 6 participants to perform an abdominal ultrasound examination with the HMD. The participants reported limitations and unfamiliarity but noted a benefit and would like to try the technology in clinical setting. According to them, the major benefits of the technology would be to facilitate navigation and improve 3D perception and its feasibility for its use in clinical practice would mainly depend on the image quality and ergonomic aspects.

Applications in vascular surgery

Some investigators aimed at developing an AR-based vascular localization system using HoloLens to allow the surgeon to precisely localize the perforator in a vascular flap transfer procedure (27). The precision of the device was tested on a 3D printed model of a volunteer's deep femoral artery and its branches in a simulated operating room and showed a goof robustness to precisely localize the vessels and the perforator, bringing hope to use it for IGS. This is corroborated by another work investigating the ability of the HoloLens to aid in the identification of surgical landmarks when performing vascular flaps of the lower extremities (28). Pre-operative CT-scans were obtained from patients and a segmentation of the skin, bone, muscle, and vascular system was performed to generate 3D-images. They were then processed and displayed in the HoloLens HMD by the surgeon using hand gesture and voice command. It allowed the visualization of virtual images of the patient's leg (including skin, bone, muscle and vessels) obtained from CT-scan. The system was tested by a surgeon in a case series of 6 patients and demonstrated precise and efficient localization of perforating vessels. The surgical team reported positive feedback and the system could potentially improve accuracy and reduce the operative time and morbidity associated with surgery. However, it is currently limited by the fact that a technical assistant is needed to help with pre-operative data preparation and to launch the application for spatial model positioning before the use by the surgeon.

Recent advances have also been achieved for image guided navigation during endovascular aneurysm repair (EVAR). In order to guide EVAR intervention in real time, some investigators created a software for visualization of the navigation with the HoloLens using CTA and an electromagnetic tracking system after attaching a sensor on the catheter tip (29). The system was tested in a human model torso that included a 3D printed patient-specific aortic model. This raise hope to develop new tools for endovascular procedures but current limits have still to be overcome. Indeed, the system requires an external marker and

improvements need to be achieved including ergonomics (comfort of use, weight of the device) and technical aspects (battery life, adaptation for the binocular visual field). Another study explored the interest of AR with holographic display during EVAR (30). Holographic data were generated from pre-operative CTA, displayed in the HoloLens, and tested in one patient undergoing AAA elective repair. The hologram could be positioned successfully in any part of the operating room and the surgeon had the possibility to move it, rotate, cut through or zoom with gesture and voice commands. It demonstrates the feasibility of the use of the device to allow 3D visualization of pre-operative data at any time during the operation and could improve the ergonomics by reducing the frequency of operator head rotation.

Applications in cardiac surgery

Applications for cardiac surgery have been tested and they could be transposed for a potential use in vascular surgery. Liu et al. developed an image guidance system to provide a 3D visual environment and a quantitative feedback of the catheter's position within the heart of the patient (31). The patient's 3D heart visualization was produced from pre-operative CT-scan and the real-time 3D position of the catheter was acquired from two fluoroscopic images taken at different angles. The 3D renderings were displayed in the HoloLens and the system was tested on a 3D printed model of a heart and spine segmented from the CT-scan. This image-guidance system brings promising perspectives for AR image-guidance to help and guide surgeons in complex anatomical cases. Another work aimed to develop a 3D visualization of myocardial scar using AR HoloLens from late gadolinium enhancement images to improve the guidance of radio-frequency ablation in the treatment of ventricular tachycardia (32). The system was tested on animal model and demonstrated the feasibility of using 3D HoloLens visualization of scar to improve magnetic resonance guided ablation of ventricular tachycardia.

HMD and smart glasses for collecting data in the operating room

The use of XR technology has also been proposed as a tool to collect medical data in the operating room. Boillat et al. investigated the feasibility of using smart glasses in the operating room to increase the benefit of surgical safety checklist (33). Surgical safety checklists have been adopted in many hospitals and they are mandatory in several countries including France or United Kingdom. Although their interest to reduce complications and mortality has been demonstrated (34, 35), the completion rate remains low due to operating rooms constraints and lack of practicality (36). The completion of surgical safety checklists was compared by four surgeons using conventional methods (n=41 checklists) or using smart glasses application with Google Glass (n=39 checklist). Interestingly, the use of smart glasses improved the completion rate to 100% (vs 76% for conventional methods) and decreased the average duration by 18%. In addition, smart glasses offered the possibility to contextualize the checklist and customize it for specific procedures and surgeons need. The use of smart glasses brings interesting perspectives to gain time and improve the relevance. It can also be of interest to improve traceability by offering the possibility to automatically transfer it in the patient's electronic medical record once completed.

Other investigators aimed to investigate the use of Smart glasses to capture images in the operating room and transfer them in the medical record (37). They compared the Google Glass application with standard digital camera to capture images from 10 patients in operating room. The application demonstrated better results over digital camera in terms of workflow efficiency including timing of image capture and uploading in medical record. The users found the application easy to learn but pointed the need of improvements before a use in practice. This included unexpected glitches, logging out in long cases, difficulty to use the voice recognition in noisy environments or limited battery life.

Current limits and future directions

HMD offer interesting perspectives for applications in vascular surgery including education, (teaching, training or telementoring) or direct use for surgical practice (pre-operative planning or image-guided surgery). Smart glasses have been tested in more restrictive settings including surgical teaching, telementoring or data collection in the operative room. Since its first launch, google had to stop the commercialization of the smart glasses for the general public due to technical issues and inadequacy with the needs of users. It has now redirected its applications toward corporations and studies performed so far pointed several current limitations for applications in surgery.

Several technical aspects need to be addressed for a use of HMD or smart glasses in clinical practice. This includes limitations due to the hardware, memory and battery life capacity. Some authors also reported unexpected glitches which could be solved, but this highlights the need to test the device in a large and various series of cases to provide a software adapted to the field reality (37). In addition, HMD has a restricted binocular field, a restricted augmentable field of view and projection size, which can limit the immersive experience (6, 38). There can also be a mismatch between focal and real distance, resulting in mismatch between real and augmented environments (39). The calibration and the launch of relevant data into the device is a critical step and although automatic processes are being developed, it often requires a technical assistant. The image quality, which is depend on the source imaging (slice thickness) can also be a limitation. The quality of image or video transmission as well as the computational time is another practical concern for the use of HMD in clinical settings. Some users reported difficulties with gesture-based control or voice commands in operating room due to ambient distraction (19, 37). Finally, efforts should be oriented toward improving the user interface to develop an easy-to-use system, customizable, that may be adapted in real

time to the patients and the clinicians need. A close collaboration between engineers and clinicians would help to develop applications that match with the expectations and the need for surgical practice.

Another concern is related to the ergonomics and the comfort of the users. HMD devices are still heavy and the weight varies between 500 g to 645 g depending on the device and manufacturer. Smart glasses weigh between 46 g to 140 g. This can cause discomfort and fatigue to the user, especially for long surgical procedures. HMD are adjusted to head size and are compatible with eye glasses. Several users also report cybersickness such as nausea, visual discomfort, dizziness, headaches, eye strains or dry eyes (8). An adjustment period and an appropriate training is also required for the operators to get familiar and use the device efficiently.

Ethical aspects are also a major consideration when investigating new devices for surgical practice. Such technology not only raises concerns for data privacy and protection but should also guarantee accuracy, safety and security for a potential use in patients. According to the European Union's General Data Protection Regulation (GDPR), the patient's consent is a main concern for the use HMD or smart glasses, as the device processes medical information. Besides, the device needs to be configured to protect the patients' data (40).

So far, a majority of the studies have been conducted in lab settings, with simulated operating rooms or virtual models, while few case series have been reported (15, 26, 28, 30, 33, 37). Launching clinical trials would be the next step to evaluate the safety and the interest of HMD in vascular surgery.

The perception of HMD by both the surgeons and the patients take a central place for a successful adoption of the technology in clinical practice. Despite proving benefits of HMD for surgical planning, data management, image-guided surgery, education, training or telementoring, clinicians expect accurate, practical and workable devices in which they can

place confidence. To evaluate the perception of the patients of wearable mounted computer devices for medical practice, a study was conducted in 96 patients (41). While most of them (73%) were unfamiliar with HMD, 76% responded it would not affect their trust in their doctor, but almost half of them were concerned about privacy and data protection. This study suggests that HMD might be well received by the general public for clinical practice, provided that it guarantees the technical and ethical mandatory requirements. Finally, the economic aspect is another concern. The cost of wearable technologies is variable depending on the device, the manufacturer and the software implemented. The cost of commercialized devices currently available ranges from 1 000 to 3 000 euros for smart glasses and from 350 euros to 3 500 euros for HMD. It mainly depends on the need of the user and its intended applications. The cost for implementation and maintenance of such systems would have to be put in balance with the clinical benefits before hoping to expand its use in common surgical practice.

Conclusion

XR technology has brought promising perspectives for applications of HMD and smart glasses in vascular interventions including education and training of surgeons, pre-operative planning, image-guided surgery or as a tool to collect medical data. The field is in its infancy and a large amount of research is needed before a potential use in daily clinical practice. Technical and ergonomics improvements are required, and barriers must be faced including ethical, economic and cultural considerations. Although the XR mountain remains steep, we believe that the challenge is worth it and could have a bright future to help surgeons and clinicians in the management of vascular interventions.

Author contribution: All authors contributed and approved the final version of the manuscript.

Acknowledgements: none

Conflict of interest: none

Funding: none

Notes: none

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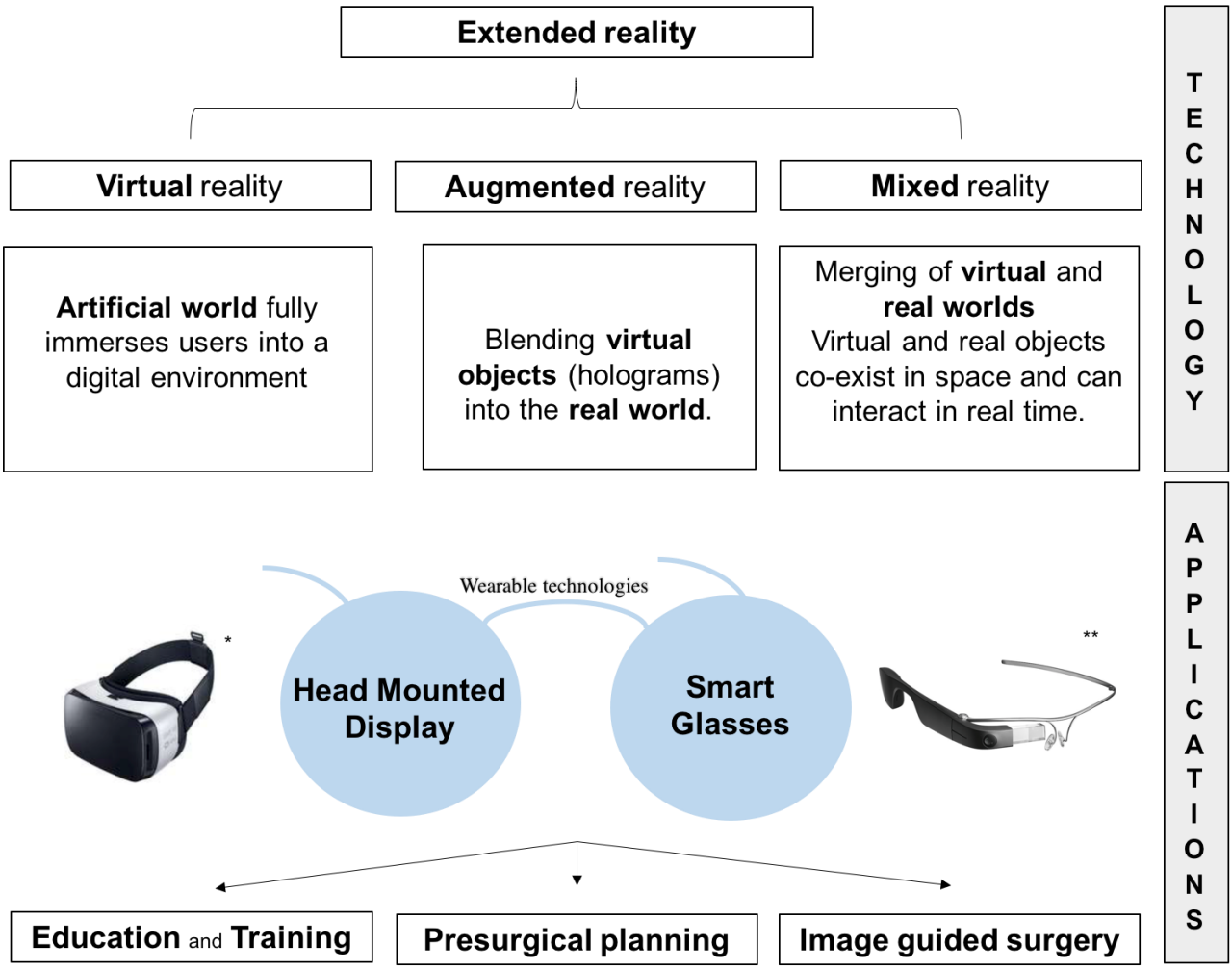

Figure 1: Implementation of Extended reality technology into head mounted displays/ smart glasses and potential applications in vascular surgery

* Head-mounted display (HoloLens, Microsoft Corporation, Redmont, WA, USA)

** Google Glass (Google, Mountain View, CA)

Field and Application	Aim	Method	Results	References
Head-mounted displays (HMD) for anatomical teaching	Assess whether learning structural anatomy utilizing VR or AR is as effective as tablet-based (TB) applications, and whether these modes allowed enhanced student learning, engagement and performance	- 59 participants were allocated 3 learning modes: VR, AR or TB - They had a lesson of skull anatomy and completed an anatomical knowledge assessment	Advantages: - No significant difference between mean assessment scores in VR, AR or TB - Increased learner immersion and engagement, interactivity, enjoyment with VR and AR Limits: - VR: participants experienced more frequently headaches, dizziness, blurred vision than AR and TB - Need to get used to VR and AR technologies: students spent more time getting familiar with the technology rather than listening to the audio stream and learning the structures	Moro et al. 2017 (8)
HMD for surgical training	Evaluate the effect of using VR surgery on the self-confidence and knowledge of surgical residents	- Use of VR experience in a multisite, single-blind, parallel, randomized controlled trial - 95 residents from 7 dental schools for training to perform a LeFort I osteotomy . 51 study group: using the immersive VR . 44 control group: using standard presentation on a laptop - Self-assessment of trainee confidence and cognitive skills	Advantages: - VR experience improved the knowledge and self-confidence of the surgical residents	Pulijala et al. 2018 (9)
HMD for surgical teaching	Investigate if a wearable surgical visualization system allowing the instructor to visualize “blind areas” in the operative field could improve trainee performance in a simulated operative setting	- 11 surgery residents who used Google glass for visualization system to place 5 needles in a simulated operative field - Video was streamed from the leaner’s system in real time to the trainer	Advantages: - Successful simultaneous visualization by the mentor and the resident even in surgery with limited exposure - Wearable surgical system did not affect mean time to task completion - Mean composite error decreased when the wearable system was deployed - Most of the participants deemed the device unobtrusive, easy to operate and useful for communication and instruction	Brewers et al. 2016 (13)
HMD for telementoring	Report a new type of AR system that integrates the Microsoft HoloLens device with 3D point tracking module for medical training and telementored surgery	- Stereo camera used to track the 3D position of a scalpel and transfer its coordinates wirelessly to a HoloLens device - Scenario of surgical training: a virtual surgical scene with pre-recorded surgical annotations is superimposed with the actual surgical scene; the surgical trainee is able to operate following virtual instructions - Scenario of telementored surgery: the virtual surgical scene is co-registered with the actual surgical scene; the virtual scalpel remotely mentored by an experienced surgeon provides the AR guidance for the inexperienced on-site operator - Evaluation of the performances of the device in benchtop experiments	Advantages: - Tracking accuracy better than 2 mm - Feasibility to use the device for AR based surgical navigation and education system Limits: - Data acquisition and transmission speed limit the real-time 3D modelling of the surgical scene	Liu et al. 2020 (14)

	Evaluate the safety of using Google Glass by assessing the video quality of a telementoring session	- 34 surgeons participated at a single institution - They were surveyed and blindly compared via video captured with Google Glass versus an Apple iPhone 5 during the open cholecystectomy portion of a Whipple.	Limits: - 50% of surgeons rated Google Glass video as fair and 50% rated it as bad to poor - Significantly greater proportion of respondents felt Google Glass video quality was inadequate for telementoring versus the Apple iPhone's (82.4 vs 26.5%, $p < 0.0001$).	Hashimoto et al. 2016 (15)

Table 1: Summary of studies investigating the use of HMD or smart glasses for education and training of surgeons

AR: augmented reality

HMD: Head-mounted displays

MR: mixed reality

TB applications: tablet-based applications

VR: virtual reality

Field and Application	Aim	Method	Results	References
Applications in general surgery	Evaluate the ease of use, physician attitudes and viability for pre-surgical planning of 2 commercially available VR applications using the vive VR headsets (HTC)	- 8 participants: residents, fellow, surgeons - Semi-structured interviews and concurrent think-aloud protocol to evaluate user satisfaction and the VR experience - 30-min usability study to accomplish tasks (i.e: selecting an image, a tool, marking a tumor, using cut planes)	Advantages - Most desired benefits from implementing VR: improving imaging of complex cases to afford better planning - Emphasis on using VR for training and patient education - Overall impression positive on the use of VR for pre-surgical planning Limits - Users reported a general sense of frustration using the applications but were appreciative of the role of VR in case planning - Gesture-based control can be confusing for some users - Building s standardized user interface for VR requires time	Napa et al. 2019 (19)
	Present a cost-effective VR application system for demonstration of 3 D virtual anatomical models	- System integrated with hand gesture interaction and voice interaction using the Oculus Rift DK2 - 10 participants evaluated the system	Advantages - VR display technology can release the mental burden - Non-contact interaction manners: facilitate the surgeons to control the model in the sterile operating room Limits - Need of a short time for the users to learn to use the device - Speed, accuracy and robustness of the technique need to be evaluated	Liu et al. 2019 (20)
	Provide researchers and practitioners initial evidence about visualization environments for immersive AR	- Compare visualization tasks with HoloLens with tangible markers, handlet tablet and traditional desktop environment - 4 tasks performed by 15 participants . Estimate spatial distance between points . Count clusters . Select visual elements . Orient a cutting plane	Advantages - Good performance for immersive tangible AR Limits - Desktop environment offered superior precision, speed, and familiarity across most tasks - Training and improvement of AR immersive technologies required	Bach et al. 2018 (21)
Applications in cardiac surgery	Examine the feasibility and initial user experience of a new mixed reality hologram platform for diagnosis and treatment plan in complex congenital heart disease	- 3D heart model segmented from CTA images in a patient with double outlet right ventricle and transposition of the great arteries - Morphological and diagnostic output from the hologram was assessed and the 3D experience was evaluated - Evaluation by 36 pediatric heart team members	Advantage - Anatomy identification and diagnostic output was high as well as rating of 3D experience - Mixed reality holograms could be useful as surgical planning tools for congenital heart disease	Brun et al. 2019 (22)

Table 2: Summary of studies investigating the use of HMD or smart glasses for pre-surgical planning

AR: augmented reality

CTA: computed tomography angiography

HMD: Head-mounted displays

VR: virtual reality

Field and Application	Aim	Method	Results	References
Head-mounted displays (HMD) for Image-guided surgery (IGS) in vascular surgery	Evaluate the precision of the HoloLens-based vascular localization system	- Precision of the localization errors tested in a simulated operating room under different conditions (with/ without light, different intensities of light, different visual angles) with a 3D printed model - Calculation of the navigation error using the coordinates of 5 pairs of points on the vascular map	Advantages: - Feasibility of the HoloLens system to precisely localize the perforator and potentially help the surgeon for vascular navigation - Mean errors were within the clinically acceptable range Limits: - The error was larger when tested with light compared with that tested without light: recommendation to use HoloLens-based surgical navigation without light.	Jiang et al. 2020 (27)
	Test the ability of the HoloLens to aid the identification of surgical landmarks when performing vascular flaps of the lower extremities	- Segmentation of the skin, bone, muscle and vascular system from CTA-scans to generate three-dimensional images and develop the HoloLens application - A surgeon tested the ability of the system to localize the perforating vessels in a case series of 6 patients with flap surgeries	Advantages: - Successful visualization of virtual images of the patient's leg anatomy and localization of perforating vessels by the surgeon Limits: - Requirement of a technical assistant to help with pre-operative data preparation and to assist with application launch and approximate spatial model positioning before involvement of the surgeon	Pratt 2018 et al. (28)
	Optimizing visualisation during endovascular aortic aneurysm repair (EVAR) using advanced navigation and augmented reality	- Guiding EVAR interventions in real-time with an electromagnetic tracking system after attaching a sensor on the catheter tip and display the information on the HoloLens device. - Test in a human model torso that includes a 3D printed patient-specific aortic model - 3D models of the phantom surface and vessels visualized with the HoloLens - Virtual angioscopy built form a CT-scan of the aortic aneurysm phantom	Advantages: - Visualization of a virtual angioscopy built from the CT-scan of the aortic aneurysm phantom - Successful visualization of the vascular navigation with the HoloLens Limits: - Need of an external marker to track endovascular tools based on attaching an electromagnetic sensor on the catheter tip - Need to improve the user interface	Garcia-Vasquez et al. 2018 (29)
	Test the application of augmented reality (AR) with holographic display and its feasibility during EVAR	- Pre-operative CTA used to create holographic data (aneurysm and bones) with the HoloLens - A surgeon tested the device in one patient undergoing elective EVAR	Advantages: - Successful visualization of the 3D data at any time of the operation by the surgeon - Possibility to interact with the virtual model: possibility to move, rotate, cut through or zoom with gesture and voice commands Limits: - Need to test the device in larger cohort of patients - Need to improve the software for imaging fusion	Rynio et al. 2019 (30)
HMD for IGS in cardiac surgery	Develop an image guidance system to provide a 3D visual environment and quantitative feedback of the catheter's position within the heart of the patient	- Pre-operative CTA used to create a patient-specific 3D heart - Real-time 3D position of the catheter acquired via two fluoroscopic images taken at different angles	Advantages: - Successful visualization of 3D images of the heart with the HoloLens device Limits:	Liu et al. 2019 (31)

		- 3D images projected in the HoloLens device	- 3D printed heart model is static and does not recapitulate the dynamic geometry and location of the heart, limiting the evaluation of the method for image-guided surgery - Improvement of automated segmentation of spine is required to apply the method in real-time on patient images	
	Develop a 3D holographic visualization of myocardial scar from the late gadolinium enhancement images on HoloLens	- Use of late gadolinium enhancement images to develop a 3D visualization of the myocardial scar in the HoloLens device - Pilot animal study performed in 5 swines who underwent controlled infarction	Advantages: - Successful 3D perception of the scar architecture with immersive experience → may help operators to facilitate magnetic resonance ventricular tachycardia ablation Limits: - Use of ex-vivo imaging in the animal study: the feasibility of the visualization with HoloLens from in-vivo images remains to be explored	Jang et al. 2018 (32)
HMD for IGS in general surgery	- Develop an AR IGS system by integration of the HoloLens	- Test the accuracy on a 3D-printed phantom model and compare it with a conventional IGS system	Advantages: - Mean error found for the placement of objects under AR guidance was similar to errors found in the literature with other AR visualization methods - Perspective to use the system for a more intuitive guidance system Limits: - Need to improve the calibration to reduce the AR visualization error - Need to improve the visualization of virtual objects to develop a more immersive experience	Meulstee et al. 2019 (24)
	- Develop a mixed-reality system combining Intel realSense sensor with HoloLens head-mounted display system for superimposing medical data onto the physical surface of a patient	- Develop an algorithm to propose a mixed-reality system to perform accurate and robust mapping from pre-operative medical images despite the presence of noise and outliers - Test on a 3D model	Advantages: - The proposed algorithm allowed to super-impose the images on the patient using mixed reality system with an accurate and robust mapping Limits: - Need to evaluate the method in real conditions	Chien et al. 2019 (25)
	Investigate the benefits and limitations of AR and head-mounted displays in ultrasound guided interventions	- Evaluate task duration and accuracy with the AR-HMD as compared to standard procedure for ultrasound-guided needle placement in 20 participants - Qualitative study to examine the user experience to perform abdominal ultrasound examination with AR-HMD in 6 participants	Advantages: - Participants placed the needles more accurately with the AR HMD - Participants noted benefits for navigation and would like to test the technology in practice Limits: - Participants did not place the needles faster with the AR HMD - Task load was not reduced - Participants reported limitations and unfamiliarity with the AR-HMD in the qualitative study	Ruger et al. 2020 (26)
	Investigate the feasibility and potential of using smart glasses in the operating room to	- 4 surgeons conducted 41 check lists using conventional methods	Advantages: - Check list completion rate with smart glasses: 100% (vs 76% with conventional	Boillat et al. 2019 (33)

Smart glasses for collecting medical data in the operating room	increase the benefit of surgical safety checklist	and 39 checklists using the smart glasses application (google glass)	methods), with a decrease in the average duration of 18% - Smart glasses improved the completion rate but also the checklist's relevance and benefits Limits: - The user tended to be more isolated and interact less from the rest of the operating room staff when using the device	
	Develop an application for Google glass to capture patient images in the operating room and securely transfer them to the electronic medical record	- Compare the application developed on Google glass with standard digital camera - 10 patients studied in operating room	Advantages: - The application performed equivalently but the standard method (digital camera) took longer to upload - Users fond the Google glass application easy to learn including log on procedure and view finder perspective Limits: - The application suffered some glitches that could be repaired with software updates	Ahmad et al. 2019 (37)

Table 3: Summary of studies investigating the use of HMD or smart glasses during surgical interventions

AR: augmented reality

EVAR: Endovascular aortic aneurysm repair

HMD: Head-mounted displays

IGS: Image-guided surgery

MR: mixed reality