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

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28 **Type of manuscript:** Review

29

30 **Abstract:**

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

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

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

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

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52

53 **Introduction**

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

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

69

70 **Fundamental concepts**

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

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

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

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

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

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

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

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

97

98 **HMD and smart glasses for education and training of surgeons**

99 *Use of HMD for anatomical teaching*

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

102 whether VR and AR could enhance student learning, engagement and performance. A total of
103 59 participants were allocated 3 learning modes: VR, AR or tablet-based applications and
104 they underwent an anatomical knowledge assessment after a lesson of skull anatomy (8).
105 While VR and AR offer an alternative to anatomical teaching on cadavers, the methods did
106 not demonstrate a significant difference on the mean assessment score compared to tablet-
107 based application. The users reported increased immersion and engagement with enjoyment in
108 using new technology, but participants using VR experienced more frequently headaches,
109 blurred vision or dizziness. They also highlighted the need of time to get used to the
110 technology during the first utilization. As XR technology tends to be more and more used in
111 daily life, it can be anticipated that they will be progressively incremented in medical and
112 surgical education within the next few decades.

113

114 *Use of HMD for surgical training*

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

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

128

129 *Use of HMD for surgical teaching*

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

140

141 *Use of HMD for telementoring*

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

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

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

165

166 *Potential applications in vascular surgery*

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

175

176 **HMD for pre-surgical planning**

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

185

186 *Applications in general surgery*

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

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

204

205 *Applications in cardiac surgery*

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

213

214 *Potential applications in vascular surgery*

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

220

221

222 **HMD and smart glasses for image-guided surgery**

223 *Applications in general surgery*

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

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

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

248

249 *Applications in vascular surgery*

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

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

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

284

285 *Applications in cardiac surgery*

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

300

301 **HMD and smart glasses for collecting data in the operating room**

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

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

325

326 **Current limits and future directions**

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

335 Several technical aspects need to be addressed for a use of HMD or smart glasses in clinical
336 practice. This includes limitations due to the hardware, memory and battery life capacity.

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

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

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

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

367 So far, a majority of the studies have been conducted in lab settings, with simulated operating
368 rooms or virtual models, while few case series have been reported (15, 26, 28, 30, 33, 37).

369 Launching clinical trials would be the next step to evaluate the safety and the interest of HMD
370 in vascular surgery.

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

375 place confidence. To evaluate the perception of the patients of wearable mounted computer
376 devices for medical practice, a study was conducted in 96 patients (41). While most of them
377 (73%) were unfamiliar with HMD, 76% responded it would not affect their trust in their
378 doctor, but almost half of them were concerned about privacy and data protection. This study
379 suggests that HMD might be well received by the general public for clinical practice,
380 provided that it guarantees the technical and ethical mandatory requirements. Finally, the
381 economic aspect is another concern. The cost of wearable technologies is variable depending
382 on the device, the manufacturer and the software implemented. The cost of commercialized
383 devices currently available ranges from 1 000 to 3 000 euros for smart glasses and from 350
384 euros to 3 500 euros for HMD. It mainly depends on the need of the user and its intended
385 applications. The cost for implementation and maintenance of such systems would have to be
386 put in balance with the clinical benefits before hoping to expand its use in common surgical
387 practice.

388

389 **Conclusion**

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

398

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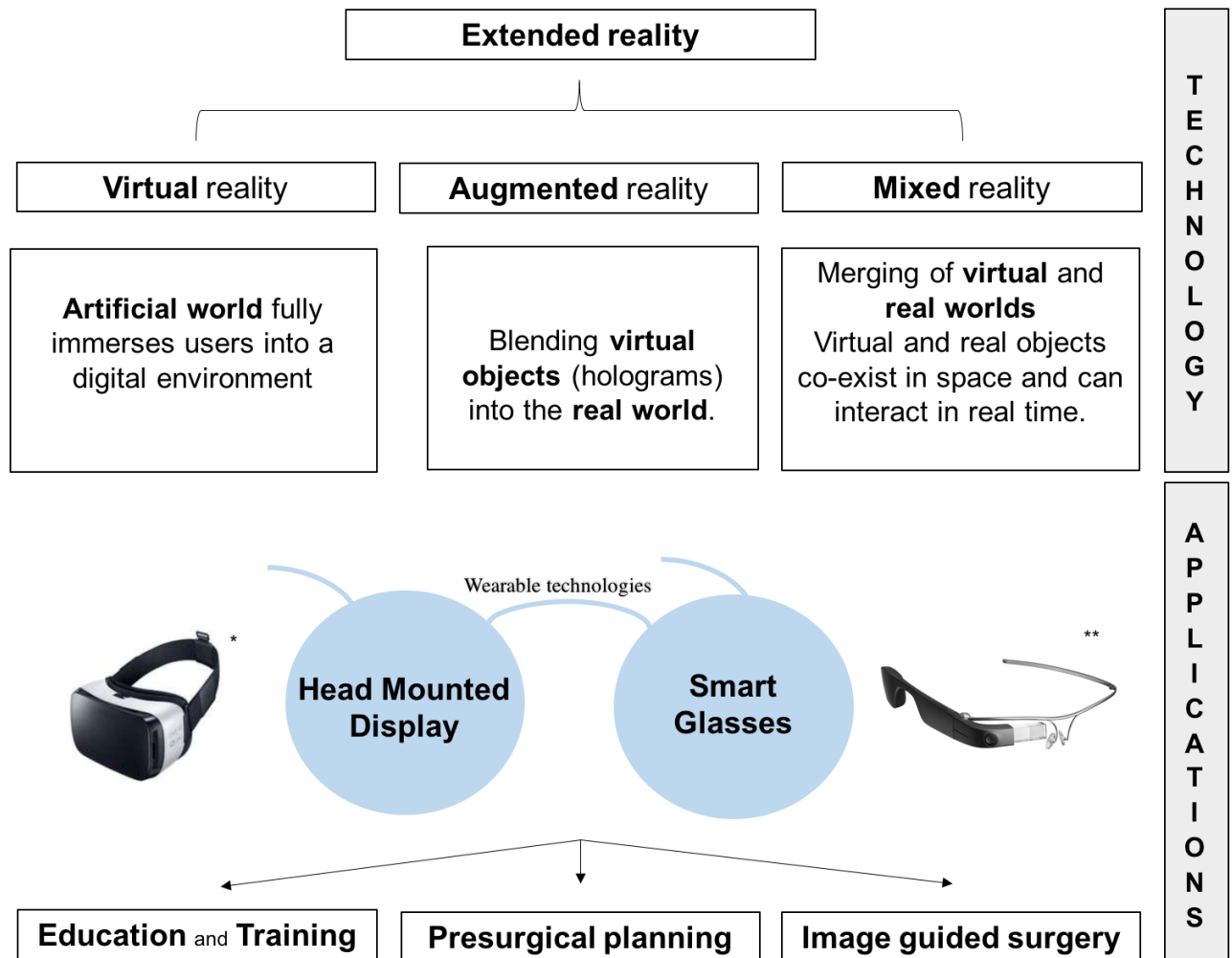


Figure 1: Implementation of Extended reality technology into head mounted displays/ smart glasses and potential applications in vascular surgery

* 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	<ul style="list-style-type: none"> - 59 participants were allocated 3 learning modes: VR, AR or TB - They had a lesson of skull anatomy and completed an anatomical knowledge assessment 	<p>Advantages:</p> <ul style="list-style-type: none"> - No significant difference between mean assessment scores in VR, AR or TB - Increased learner immersion and engagement, interactivity, enjoyment with VR and AR <p>Limits:</p> <ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 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 <ul style="list-style-type: none"> . 51 study group: using the immersive VR . 44 control group: using standard presentation on a laptop - Self-assessment of trainee confidence and cognitive skills 	<p>Advantages:</p> <ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 11 surgery residents who used Google glass for visualization system to place 5 needles in a simulated operative field - Video was streamed from the learner’s system in real time to the trainer 	<p>Advantages:</p> <ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 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 	<p>Advantages:</p> <ul style="list-style-type: none"> - Tracking accuracy better than 2 mm - Feasibility to use the device for AR based surgical navigation and education system <p>Limits:</p> <ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 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: <ul style="list-style-type: none"> - 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)
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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)	<ul style="list-style-type: none"> - 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) 	<p>Advantages</p> <ul style="list-style-type: none"> - 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 <p>Limits</p> <ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - System integrated with hand gesture interaction and voice interaction using the Oculus Rift DK2 - 10 participants evaluated the system 	<p>Advantages</p> <ul style="list-style-type: none"> - VR display technology can release the mental burden - Non-contact interaction manners: facilitate the surgeons to control the model in the sterile operating room <p>Limits</p> <ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - Compare visualization tasks with HoloLens with tangible markers, handlet tablet and traditional desktop environment - 4 tasks performed by 15 participants <ul style="list-style-type: none"> . Estimate spatial distance between points . Count clusters . Select visual elements . Orient a cutting plane 	<p>Advantages</p> <ul style="list-style-type: none"> - Good performance for immersive tangible AR <p>Limits</p> <ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 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 	<p>Advantage</p> <ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 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 	<p>Advantages:</p> <ul style="list-style-type: none"> - 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 <p>Limits:</p> <ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 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 	<p>Advantages:</p> <ul style="list-style-type: none"> - Successful visualization of virtual images of the patient's leg anatomy and localization of perforating vessels by the surgeon <p>Limits:</p> <ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 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 angiography built from a CT-scan of the aortic aneurysm phantom 	<p>Advantages:</p> <ul style="list-style-type: none"> - Visualization of a virtual angiography built from the CT-scan of the aortic aneurysm phantom - Successful visualization of the vascular navigation with the HoloLens <p>Limits:</p> <ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 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 	<p>Advantages:</p> <ul style="list-style-type: none"> - 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 <p>Limits:</p> <ul style="list-style-type: none"> - 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	<ul style="list-style-type: none"> - 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 	<p>Advantages:</p> <ul style="list-style-type: none"> - Successful visualization of 3D images of the heart with the HoloLens device <p>Limits:</p>	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 found 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