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Next-generation Virtual and Augmented Reality in Surgical Education: A Narrative Review

SHARAF SHEIK-ALI, MBBS, BSC
ACADEMIC FOUNDATION DOCTOR
OXFORD CLINICAL ACADEMIC GRADUATE SCHOOL
UNIVERSITY OF OXFORD, OXFORD, UK

HILARY EDGCOMBE, BM, BCH (OXON), FRCA (LON), MSC
GLOBAL HEALTH (KCL)
CONSULTANT ANAESTHETIST
NUFFIELD DEPARTMENT OF CLINICAL NEUROSCIENCES (NDA)
UNIVERSITY OF OXFORD, OXFORD, UK
NUFFIELD DEPARTMENT OF ANAESTHETICS
OXFORD UNIVERSITY HOSPITALS NHS FOUNDATION TRUST
OXFORD, UK

CHRIS PATON, MBBS, MBA
HEAD OF THE GLOBAL HEALTH INFORMATICS GROUP
CENTRE FOR TROPICAL MEDICINE AND GLOBAL HEALTH
UNIVERSITY OF OXFORD, OXFORD, UK
NUFFIELD DEPARTMENT OF MEDICINE
UNIVERSITY OF OXFORD, OXFORD, UK

ABSTRACT

Background: Virtual and Augmented Reality (VR/AR) has been used in surgery for several decades. Over the past 5-10 years, however, new technological advances, including high-resolution screens, mobile graphical processing units (mGPUs) and position-sensing technologies, have been incorporated into relatively low-cost VR and AR devices. This review focuses on the current impact of the application of these "Phase 2" VR/AR technology in surgical training.

Methods: A narrative literature review was undertaken using PubMed and Web of Science to identify comparative studies related to the impact of Phase 2 VR or AR tools on surgical training, defined in terms of the acquisition of technical surgical skills. Eleven studies on the effectiveness of VR/AR in surgical education were identified for full review. Further, the grey literature was searched for articles describing the current state of VR/AR in surgical education. A quality analysis using the Newcastle Ottawa scale showed a median score of 7 (out of a maximum achievable score of 9)

Results: All studies showed a positive association between the use of VR/AR in surgical training and skill acquisition in terms of improving the speed of acquisition of surgical skills, the surgeon's ability to multitask, the ability to perform a procedure accurately, hand-eye coordination and bimanual operation. The grey literature presented a common, positive theme of the benefits of VR/AR in surgical training.

Conclusions: Based on the limited evidence available, VR/AR appears to have positive training benefits in improving the speed of acquisition of surgical skills. However, the significant heterogeneity in study methodology and the relative recency of wider VR/AR adoption in surgical training mean that only tentative conclusions can be drawn at this stage. Further research, ideally with large sample sizes, robust outcome measures and longer follow-up periods, is recommended.

INTRODUCTION

Surgical training both develops and requires considerable manual dexterity. Much of this skill is acquired through theatre exposure and practice. Currently, in the United Kingdom, the training pathway incorporates an outcome-based approach for the achievement of core surgical competencies (Intercollegiate Surgical Curriculum Programme).[1,2] The role of virtual and augmented reality (VR/AR) in improving and assessing these competencies has been presented as being potentially beneficial for both the trainee and the assessor.[1] In view of the rapid development of accessible and affordable VR/AR technology over the past five years, we review the impact of and evidence for new-generation "Phase 2" VR/AR products in surgical education.

VR and AR have been used in surgery for several decades.[2] However, prior to the ubiquity of affordable smartphones, they had relatively limited uptake. Early Phase 1 VR products required external computing power sources and had limited graphics performance, which limited their use in surgery.[2] Over the past five years, however, technological developments from the smartphone industry, including high-resolution screens, mobile graphical processing units (mGPUs) and position-sensing technologies, have been incorporated into relatively low-cost VR/AR headsets, so-called Phase 2 products. Phase 2 products incorporate high-speed technologies that require less power to run and cost less. There are two main types of Phase 2 devices. The first type uses low-cost headsets that hold an actual smartphone in front of the user's eyes and use the smartphone's hardware and software to deliver the VR experience. The second type uses smartphone components (such as high-resolution screens and mGPUs), but incorporate them as VR/AR headsets that either need to be attached to a computer via a cable or can operate as self-contained headsets. As these devices have become both more powerful and more widely accessible,[3] the adoption of VR and AR technologies by surgeons and trainees has also increased. Examples of such use include hardware devices worn intraoperatively, applications on smart phones that simulate surgical procedures, headsets worn to augment the in-theatre experience and haptics to augment the sense of touch in a surgical setting.

Since their release, Phase 2 VR products have been adopted into surgical training at a somewhat faster rate than Phase 1 products, as they provide more immersive and realistic surgical situations, offer the potential for wide-scale adoption of virtual reality approaches, and cost far less.[2,4] Nonetheless, in contrast to other contexts, notably the aviation industry, the use of VR for surgical training has not yet been widely recognised, and understanding of its potential benefits and misuse is limited, partly reflecting the previous limitations of Phase 1 products.[5] Additionally, recent developments in VR technology have not been widely discussed in the medical literature. Industry announcements and documentation of the adoption of new devices and platforms are largely covered by technology-focused websites, mass media and industry-focused reports and white papers. This "grey" literature, defined as research or information produced outside of conventional academic publications and distribution channels, offers relevant information on the potential of new VR hardware and platforms.

To understand the potential of new VR technology for surgical education, it is necessary both to understand the current state of technological development (largely through non-academic grey literature) and the best evidence relevant to the effectiveness and roles of previous forms of VR and training in surgical practice (available within the academic literature). Therefore, this review focuses on the application of VR/AR in surgical education using both academic (comparative papers) and grey literature to determine the impact of currently available Phase 2 VR/AR technology in surgical training.

METHODS

A narrative literature review was undertaken for studies related to the impact of Phase 2 VR/AR tools on surgical training. For the purposes of this review, we focused on surgical training with respect to the acquisition of technical surgical skills. Papers published before 2009 were excluded to focus as much as possible on the implementation of Phase 2 VR/AR products.

Academic literature search

PubMed and Web of Science were searched on 26 February 2019 for articles published between January 2009 and February 2019. The search terms used were "virtual reality", "augmented reality" and "surgical training". Titles and abstracts were then reviewed by the lead author to identify papers relevant to the research aim. The remaining studies were read in full and irrelevant studies were excluded, along with papers published before 2009. Figure 1 summarises the search strategy.

Articles on the application of VR or AR in surgical education were eligible for inclusion. Comparative studies, narrative and systematic reviews, or short articles were eligible to be included. There was no language restriction.

Data extracted included author, study type, number of participants, study design and methodology, primary outcome and results of the study. The technology used in each study was also identified. Where possible, the quality of included studies was analysed via an adapted version of the Newcastle Ottawa scale (which includes criteria related to participant selection, comparability and outcome). The maximum score possible was 9. Selection was defined as how well the authors selected participants to the study who represented surgeons or surgical trainees. Comparability described how well the controls were similar to the study group. Outcome was defined as the accuracy of assessment and relevance to surgical trainees. Academic papers that did not include a comparison were reviewed and relevant findings are presented.

Grey literature search

We adopted the approach to searching the grey literature described by Mahood et al.,[6] which involves systematically searching resources where the grey literature is predominant: online databases and conference proceedings, i.e., abstracts, web search engines and the library catalogue. Additionally, we searched Google™ and Yahoo™ with the phrases "virtual reality", "augmented reality" and "surgery" on 29 April 2019. The first 50 pages of results from both sites were assessed against the inclusion criteria. These included company and industry repositories, abstracts of oral and poster presentations, media reports and clinical trial registries. Duplicates were removed, along with advertisements and forums. Conference proceedings were examined for posters or abstracts that involved virtual reality or augmented reality in surgical practice. This was done through an online search adding the term "conference" to the search criteria above.

RESULTS

Academic literature

Eleven studies that examined the effectiveness of VR/AR in surgical education were identified for full review (Tables I-III). All of these studies involved the application of VR/AR in surgical education. The results of a quality analysis are summarised in Table IV: the median score was 7 (maximum achievable score of 9). No study scored less than 6. Almost all of the studies scored well for selection (mean 3.5/4). The measurement of outcome criteria had the lowest average score (1.8/3), mainly because different methods were used to assess technical surgical skill.

Of the 11 studies, seven were randomized control trials.[7-13] All seven showed a positive association between skill acquisition and the use of VR/AR in surgical training. The remaining studies were observational or prospective cohort studies, and showed a positive correlation between VR/AR and improvements in surgical training.[14-18]

Studies that were notable for clear outcomes included Pulijala et al.,[7] Feifer et al.,[8] Larsen et al.[9] and Bongers et al.[10] The studies had a wide range of participants and their approaches to assessing outcome were notable for their uniformity.

Grey literature

Web searches were conducted using the Google™ and Yahoo™ search engines (accessed 26 February 2019). Duplicates and irrelevant articles were excluded. The websites of companies that currently produce VR/AR technology for use in surgery were also reviewed. We identified 6 media outlets that focused on the potential of VR/AR in surgical education and application in theatre. Four poster abstracts were also identified, each of which focused on the application of VR to one area of surgery. The details of 2 clinical trials that are currently examining the use of AR to improve the acquisition of procedural skills in polypectomy and the potential impact of VR/AR in physiotherapy were also identified.

While all of the media outlets explored (Euronews, MobiHealthNews, The Telegraph, HealthcareEurope, Vascular News, NRI Digital, Royal College of Surgeons web site) suggested that VR/AR would have a positive role in surgical training,[19-25] there were no significant data to support these claims.

Four poster abstracts that were presented at conferences and available online were identified.[26-29] Virtual reality was shown to be effective for assessing surgical skill in simulators that replicated performing an appendectomy, an orthopaedic trauma situation and upper-limb surgery.[26,27]

Two clinical trials were also identified through a search of ClinicalTrialsUK on the use of VR/AR in surgical education.[30,31] The first study, a randomized control trial that is currently underway, aims to evaluate the effect of

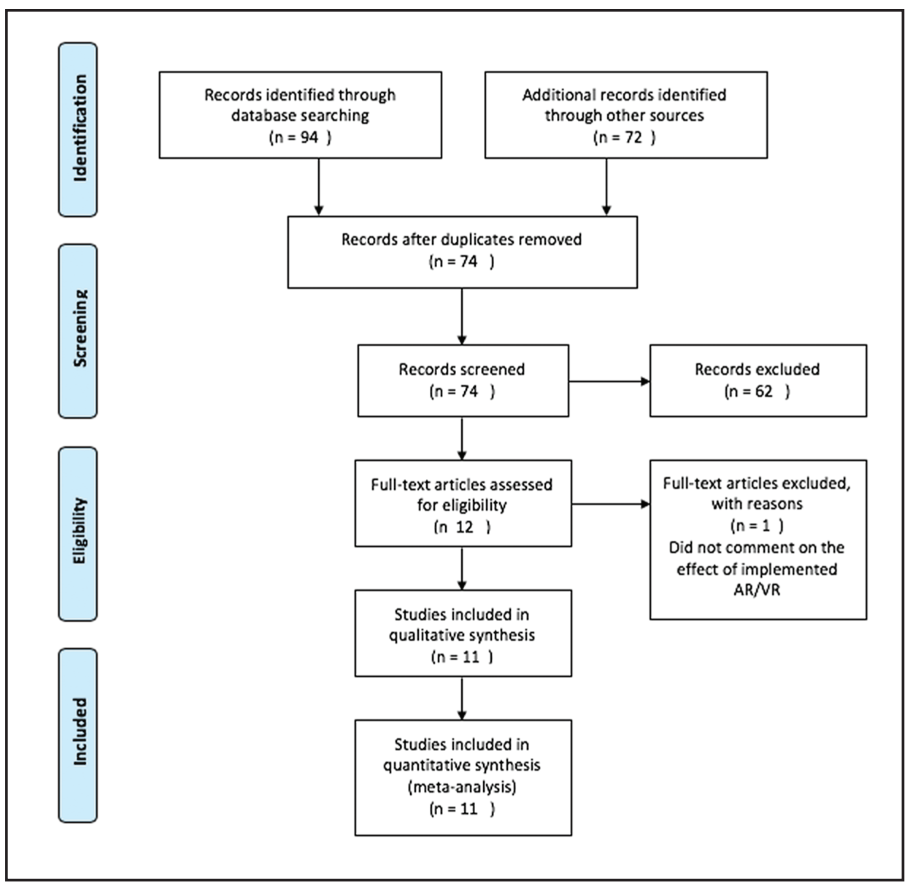

Figure 1. Academic literature search.

Table I
Studies selected from the academic literature

Author/ Year	Study type	Participants	Primary outcome	Conclusions
Pulijala et al. 2018[7]	RCT	51 dental residents (Intervention) 41 dental residents (Control)	Linkert scale self-assessment scores of trainee confidence after performing a Lefort 1 Osteotomy.	Significantly greater perceived self-confidence levels compared to those in the control group (P = .034; $\alpha = 0.05$).
Feifer et al. 2011[8]	RCT	20 medical students (Intervention) 5 medical students (Control)	Precision, speed, smoothness, and degree of damage to surrounding tissue when performing 4 surgical procedures (peg transfer, pattern cutting, extracorporeal/ intracorporeal suturing and cannulation)	Statistically significant performance enhancement for all four robotic tasks in the groups receiving dual training (P < 0.05).
Larsen et al. 2009[9]	RCT	11 new medical students (Intervention) 10 new medical students (Control)	Technical performance assessed by two independent observers according to procedure validated general and task-specific rating scale (18)	The simulator-based group had a greater median total score on the rating scale. The median operation time in the simulator group was 12 min vs. 29 min in the control group.
Bongers et al. 2015[10]	RCT	42 MD and PhD students	Time to solve insufflator problems; a measurement of the ability of the candidate to be able to switch tasks from laparoscopic suturing to solving insufflator problems.	The intervention group was significantly faster at solving insufflator problems (mean = 1.60Log(s) vs. 1.70Log(s), P = 0.02).
Vera et al. 2014[11]	RCT	19 pre-medical and medical students. Augmented Reality Telementoring (ART) (n = 10). Traditional mentoring (n = 9)	The time to perform an intracorporeal suturing task was assessed after training by either ART or traditional mentoring.	The ART group required less time than the traditional group (mean 167.4 vs. 242.4 s, P = 0.014).
Lahanas et al. 2015[12]	Observational	10 Novices with no experience in laparoscopic surgery and 10 experienced surgeons.	Tasks were performed using AR technology while measuring execution time, tool pathlength, instrument navigation, peg transfer and clipping	Between-group comparison demonstrated highly significant differences (<0.01) in all performance metrics
Orzech et al. 2012[13]	RCT	24 surgical residents. Virtual reality or Box trainer.	After training with either VR or a box trainer, technical proficiency (including suturing time+outcome) was assessed by 2 independent observers using 2 validated tools.	No significant differences in laparoscopic suturing in the OR were found between the 2 groups with respect to time (P = 0.74), global rating score (P = 0.65) or checklist score (P = 0.97) VR training was more efficient than box training (transfer effectiveness ratio of 2.31 vs. 1.13)
Bharathan et al. 2013[14]	Prospective Cohort Study	25 novice trainees and 9 senior gynaecologists.	Assessment of salpingectomy task: dexterity metrics were captured by the simulator, including total time, total path length and total number of movements in performing salpingectomy.	Significant differences were observed among experienced, intermediate and novice gynaecologists in terms of time taken (median 170 vs. 191 vs. 313 s (P = 0.003) respectively) and total number of movements (median 200 vs. 267 vs. 376 P = 0.045)

Table I (continued)
Studies selected from the academic literature

Author/ Year	Study type	Participants	Primary outcome	Conclusions
Nugent et al. 2013[15]	Prospective Cohort Study	26 novice surgeons	After training with an AR simulator and laparoscopic equipment, locating and coordinating intraoperatively, object positioning and manipulation of a sharp object were measured.	All 26 novice surgeons significantly improved in performance with repetition for the metrics of time ($P < 0.001$) and motion analysis ($P < 0.001$).
Moult et al. 2013[16]	Prospective Clinical Study	51 fellows and residents	The accuracy of thoracic pedicle screw placement was evaluated after training with an AR simulator with haptic feedback.	Accuracy improved after practice sessions ($P = 0.04$).
Luciano et al. 2011[17]	Prospective Clinical Study	51 fellows and residents	The accuracy of thoracic pedicle screw placement was evaluated after training with an AR simulator with haptic feedback.	Accuracy improved after practice sessions ($P = 0.04$).
Shakur et al. 2015[18]	Prospective Cohort Study	71 residents provided their PGY-level and simulator performance data	Using a virtual reality percutaneous trigeminal rhizotomy simulator, the mean distance from the ideal entry point and the distance from the target site were used to calculate a final surgical assessment score.	The mean distance from the entry point (9.4 mm vs. 12.6 mm, $P = .01$), the distance from the target (12.0 mm vs. 15.2 mm, $P = .16$), and the final score (31.1 vs 37.7, $P = .02$) were lower in senior residents than in junior residents.

Table II
Technologies used in the studies

Author/Year	Technology
Pulijala et al. 2018[7]	Oculus Rift (Facebook Technologies, LLC, Menlo Park, CA) with a Leap Motion device (Leap Motion, Inc., San Francisco, CA)
Feifer et al. 2011[8]	Laparoscopic simulation programs, LapSim® (Surgical Science Sweden AB), and ProMIS® (Haptica, Ireland)
Larsen et al. 2009[9]	Proficiency-based virtual reality simulator training
Bongers et al. 2015[10]	Virtual-reality (VR) laparoscopic skills simulator
Vera et al. 2014[11]	Augmented reality telementoring (ART) platform.
Lahanas et al. 2015[12]	Box-trainer, a camera and a set of laparoscopic tools equipped with custom-made sensors that allow interaction with VR training elements
Orzech et al. 2012[13]	Virtual reality (VR) simulator or box trainer
Bharathan et al. 2013[14]	The LAP Mentor™ VR laparoscopic simulator (3D Systems, Littleton, CO)
Nugent et al. 2013[15]	Augmented reality laparoscopic simulator
Moult et al.2013[16]	Perk Tutor (open source) - an augmented reality training system for US-guided needle insertions in a configuration for percutaneous procedures of the lumbar spine.tions in a configuration for percutaneous procedures of the lumbar spine.
Luciano et al. 2011[17]	High-performance augmented reality and haptic technology workstation.
Shakur et al.2015[18]	A real-time augmented reality simulator for percutaneous trigeminal rhizotomy was developed using the ImmersiveTouch™ platform (3D Systems).

Table III
Skills developed

Skills	Authors
Multitasking	Bongers et al. 2015[10]
Time (Reduced time in peforming a given procedure)	Larsen et al. 2009,[9] Bongers et al. 2015,[10] Vera et al. 2014[11]
Accuracy in performing a procedure	Orzech et al. 2012,[13] Luciano et al. 2011[17]
Perception of depth of field, hand-eye coordination and bimanual operation	Lahanas et al. 2015,[12] Vera et al. 2014[11]
Speed of skill aquisition	Vera et al. 2014,[11] Shakur et al. 2015[18]

AR on the acquisition of procedural skills in a simulation-based training curriculum for polypectomy.[30] The second study will examine the impact of VR/AR on patient recovery, specifically on physical therapy.[31]

DISCUSSION

Six large companies have each invested heavily in the application of VR/AR in healthcare (Table V). The market for VR/AR in healthcare is estimated to reach 6141.78 million USD by 2025.[32]

In this review of the academic and grey literature, there was an overall positive association between improved surgical education and the use of virtual or augmented reality (VR/AR). The studies reviewed demonstrate that VR/AR may be useful for increasing practical skills as well as surgical knowledge, at least in the short term.

The VR/AR tools tested included VR headsets, box trainers that assessed suturing skills, simulators and immersive touch platforms. This variation in available tools demonstrates the breadth of the impact that VR/AR can have on improving surgical training. However, it also makes it difficult to compare studies, not just because of the different tools used, but also because of the different methodologies in each study. Nonetheless, two main prospects for VR/AR were identified in the studies examined: as an assessment tool and as a skill-acquisition tool.

VR/AR in the assessment of surgical skills

It can be very difficult to assess surgical skills.[33] While workplace-based assessments theoretically provide objective feedback and evidence that competencies for progression to the next stage of training have been achieved, they have their limitations.[34] The objectivity of the results can depend heavily on the assessor's interpretation and bias. Several studies have reported the beneficial and objective use of VR/AR as a tool for assessing surgical skills. Lahanas et al.[12] showed that a virtual reality box trainer can significantly distinguish between suturing skills of experienced and inexperienced surgeons and can be a valid assessment tool.

Table IV
Adapted Newcastle Ottawa Scale - Quality Analysis

Author/Year	Study	Selection (/4)	Comparability (/2)	Outcome (/3)	Total (/9)
Pulijala et al. 2018[7]	RCT	4/4	2/2	2/3	8/9
Feifer et al. 2011[8]	RCT	4/4	1/2	2/3	7/9
Larsen et al. 2009[9]	RCT	4/4	2/2	2/3	8/9
Bongers et al. 2015[10]	RCT	4/4	2/2	2/3	8/9
Vera et al. 2014[11]	RCT	3/4	1/2	3/3	7/9
Lahanas et al. 2015[12]	Observational	3/4	2/2	2/3	7/9
Orzech et al. 2012[13]	RCT	4/4	2/2	2/3	8/9
Bharathan et al. 2013[14]	Prospective Cohort Study	3/4	1/2	1/3	5/9
Nugent et al. 2013[15]	Prospective Cohort Study	4/4	1/2	1/3	6/9
Moult et al. 2013[16]	RCT	3/4	1/2	2/3	6/9
Luciano et al. 2011[17]	Prospective clinical study	3/4	2/2	1/3	6/9
Shakur et al. 2015[18]	Prospective Cohort Study	3/4	2/2	2/3	7/9
Average		**3.5/4**	**1.6/2**	**1.8/3**	**6.9/9**
Median		**3/4**	**2/2**	**2/3**	**7/9**

Table V
Companies that have invested in the application of VR/AR in healthcare

Company	Involvement in surgical training
Microsoft HoloLens (Microsoft Inc., Redmond, WA)	HoloLens allows surgeons to take existing CT scans and overlay 3D digital models of them onto a patient's limb during reconstructive surgery.
Samsung Gear VR (Samsung Electronics Co., Ltd., Seoul, Republic of Korea)	Trainee surgeons can watch complex operating procedures live via a headset, with interactive content that provides additional patient data during the operation
Oculus (Facebook Technologies, LLC, Menlo Park, CA)	RCSI medical training simulator. Interactive app that allows trainees to experience and simulate a trauma scenario and make timely critical decisions
Oculus Rift (Facebook Technologies)	Simulators - various interactive games to simulate surgery such as knot-tying, suturing and trauma scenarios.
PlayStation® VR (Sony Interactive Entertainment LLC, San Mateo, CA)	Simulators - various interactive games to simulate surgery such as knot-tying, suturing and trauma scenarios.
Google Daydream (Google LLC, Mountain View, CA)	Compatible with mobile phones, low-cost simulators and visualisation of live stream operations
Google Cardboard (Google)	Compatible with mobile phones, low-cost simulators and visualisation of live stream operations
Apple AR (Apple Inc., Cupertino, CA)	iOS - used in medical education; 3D interactive anatomy visualisation.

VR/AR in the acquisition of surgical skills

VR/AR has been shown to be effective for training surgeons in both simple and complex procedures. Augmented or VR laparoscopic box simulators appear to enhance widely used laparoscopic box trainers for the acquisition of surgical skills. Nugent et al.[15] showed that when 26 novice laparoscopic surgeons trained with AR laparoscopic box simulators, their technical skills improved with respect to both performance time and motion analysis. Further, Luciano et al.[17] demonstrated that surgical trainees performing complicated procedures can improve their manual dexterity through the use of AR haptic technology devices. There was a significant improvement ($P = .04$) in performance accuracy from practice to test sessions. This supports the notion that repetition in training can improve surgical dexterity and manual handling without having a direct negative impact on the patient.

Limitations of the review

While the published studies described positive results regarding the use of VR/AR technologies in surgical training, the small sample sizes and length of follow-up mean that further research will be needed to confirm these findings. Wide methodological variability also limits our ability to compare studies at this stage.

Most work to date has not addressed two important issues. Firstly, there has been no cost-benefit analysis, which is potentially an important factor in the uptake of new technology to enhance learning.[3] The annual cost of training 5 residents on a laparoscopic box trainer was reported to be 11,975 USD, which is less than similar training on a VR simulator (17,380 USD).[13] The cost of VR/AR training will need to be weighed against the promise of improved speed of skill acquisition. Secondly, the implications for data management, including ownership and confidentiality (where patients are included), as well as infrastructural requirements should also be considered in the large-scale implementation of new data-heavy technologies.

This review included all surgical fields. However, the value of VR/AR technology could be subspecialty-related. For example, trainees in urology, a branch of surgery that uses endoscopic and robotic techniques for many procedures, might benefit more by using VR/AR in skill acquisition and performance than trainees in other specialties.[35] It is no surprise that robotic training in simulated environments has been implemented rapidly into urology training programs.[36] The literature is still too sparse to allow meaningful comparisons of VR/AR training in different subspecialties. To warrant its place as an effective surgical training tool, VR must convincingly represent both the reality of operating and the (sometimes complex) variation between different patients.

Technical skills are a small part of surgical training. Other important aspects, including management, interpretation, examining and decision-making, were not addressed in our study. This study only searched 2 databases for comparative studies after 2009. Studies performed before 2009 that included Phase 2 VR/AR products may not have been included. Furthermore, this study did not include editorials or comments that may have added to the literature. The overall limitations of the grey literature include a lack of coherent detail on the effectiveness of VR/AR technology on surgical training/performance.

CONCLUSION

The limited evidence available suggests that VR/AR may have positive training benefits in improving the speed of acquisition of surgical skills, the ability of surgeons to multitask, the ability to perform a procedure accurately, hand-eye coordination and bimanual operation. However, the variation in study methodology and the relative recency of wider VR/AR adoption in surgical training means that we can only draw tentative conclusions at this stage. Further research, ideally with larger sample sizes, robust outcome measures and longer follow-up periods, is recommended.

Although this study was limited in scope to examining the effectiveness of VR/AR training at improving technical skills in surgery, we recognise the importance of considering wider implementation issues as these technologies are already being informally adopted at local institutions. It will be important to develop an early framework for a VR/AR surgical curriculum that incorporates full accountability and transparency for its effectiveness, cost and impact. STI

AUTHORS' DISCLOSURES

CP is a director and shareholder of New Media Medicine Ltd. which provides digital health and medical e-learning consultancy and development services. CP is also the Co-Principal Investigator of the LIFE (Life-saving Instruction For Emergencies) project, which has received funding from the Skoll Foundation, Médecins Sans Frontieres, Saving Lives at Birth (USAID, DFID, Bill and Melinda Gates Foundation, KOICA and Grand Challenges Canada), Wellcome Trust, HTC and GCRF.

The other authors declare that they have no conflicts of interest.

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