Exploring the Roles of Extended Reality Technologies in Advancing Colorectal Surgical Training

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ABSTRACT

Extended reality (XR) is an umbrella term for technologies that incorporate digital and physical elements to alter a user's experience, namely: Augmented Reality (AR); Virtual Reality (VR); and Mixed Reality (MR). With National Health Service (NHS) waiting lists at record levels, a shortage of trained endoscopists within the United Kingdom, and a greater likelihood of nonstandard training outcomes following the COVID-19 pandemic, there is a requirement for significant developments in colorectal surgical training.

AR has useful applications within both simulation training and intra-operative guidance, such as image overlays and conceptualisation. Both AR and VR offer three-dimensional reconstruction of radiological images, thereby allowing for enhanced appreciation and visualisation of anatomical structures. There is, however, a much greater evidence base for the validity of VR within the sphere of colorectal surgical training; primarily for simulation with respect to endoscopy, laparoscopy, and robotics. MR is a developing field with technological advancements allowing for a combination of AR and VR.

Potential advantages of XR teaching over conventional approaches include: integration with artificial intelligence; objective assessments; immediate feedback; a wider exposure to pathologies and procedures; and potential downstream safety benefits to patients. Environmental and socioeconomic factors require further evaluation with the potential for meta conferences or meta hospitals. Disadvantages may include a lack of focus on patient communication skills and the lack of standardised XR training protocols. These technologies have an exciting future in serving as adjuncts to colorectal surgical training.

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Key Points:

- Extended reality (XR) — encompassing Augmented Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) — presents significant potential to enhance colorectal surgical and endoscopic training by offering accessible, efficient, and robust simulation environments.
- AR can improve intra-operative outcomes by improving surgical navigation, this effect is enhanced with integration of AI.
- VR provides realistic simulations for laparoscopic, endoscopic, and robotic procedures, with validity demonstrated in replicating in vivo surgical skills and improving trainee performance.

• MR technologies are undergoing constant development and may improve anatomical visualisation during surgery as well as trainee proficiency in specific tasks.
• XR offers numerous advantages over traditional training methods, including: objective assessments; immediate feedback; exposure to diverse scenarios; increased patient safety; and improved environmental sustainability.
• Limitations of XR include high implementation costs, a potential lack of focus on non-technical skills, and the need for standardisation within training.
• Future applications of XR may include integration within curricula, objective assessments, and remote examinations, thereby potentially transforming the surgical training landscape.

BACKGROUND

Extended reality (XR) is an umbrella term for technologies that alter a user's experience of the physical world by incorporating various degrees of digital elements (Figure 1). The simplest form of these technologies is 'Augmented Reality' (AR); this is where real world information is viewed and interacted with while a digital overlay is applied. Contrastingly, 'Virtual Reality' (VR) immerses users fully in a digital-only space with no feedback from the physical world. Finally, 'Mixed Reality' (MR) represents an amalgamation of the two aforementioned technologies, allowing users to switch between, or interact simultaneously with, both the physical and digital worlds.

Colorectal surgery has seen a paradigm shift in recent decades. The era of open surgery was replaced by the minimally invasive revolution. Laparoscopy was first utilised in colorectal surgery in 1991, with a case series of laparoscopic colectomies[1]. A decade later, the first robotic series was reported[2]. With these advancements in technology, a concomitant requirement for training ensued. The initial transition from open to laparoscopic surgery incurred several issues. Consultant learning curves of three years before starting to train trainees, combined with dual consultant operating in over a third of cases were reported[3]. These same factors, noted in 2008, are now returning with the increased utilisation of robotic surgery. A combination of poor trainee perceptions, consultants performing favourable training cases, and requirements for trainees to bedside assist[4], underpin this lack of training opportunities. These are further compounded by the effects of the COVID-19 pandemic. Analysis of Annual Review of Competency Progression (ARCP) for United Kingdom (UK) general surgical trainees highlighted an odds ratio of 3.07 for receiving a nonstandard outcome compared with pre-pandemic levels[5]. The COVID-19 pandemic was associated with a 30% reduction in operating room exposure[6] as well as significantly higher anxiety levels among surgical trainees[7].

In addition to surgical training issues, endoscopy training has been historically difficult for NHS trainees due to limited resources and service provision pressures[8]. In 2013, the National Health Service (NHS) began operating an endoscopic colorectal cancer screening programme to all men and women over the age of 55[9]. Due to a shortage of trained endoscopists within the NHS workforce, low patient acceptance, and building pressures from the COVID-19 pandemic, this service was discontinued on 13th January 2021[10]. In an attempt to combat the rising need for endoscopists, the Joint Committee on Surgical Training (JCST) mandated a curriculum change for colorectal surgical trainees. A shift from no prior requirement to a requirement of 200 colonoscopies was introduced to attain a Certificate of Completion of Training (CCT). This is in addition to an already trainee-reported deficiency with respect to endoscopic training[11-13].

Thus, there is a significant need for more accessible, efficient, and robust training for not only endoscopy, but also minimally invasive surgery within the UK. However, NHS waiting lists are at record levels with almost 8 million patients awaiting hospital treatment[14]. As of November 2024, 41.9% of incomplete non-urgent referrals to general surgery surpassed the recommended 18 weeks Referral to Treatment (RTT) target[15]. Consequently, there is an unmet need for adjuncts to training, which could even occur outside the operating theatre. The Halstedian approach of 'see one, do one, teach one 'may benefit from the digital surgery revolution. This review explores the roles that XR technologies may offer in advancing colorectal surgical training.

AUGMENTED REALITY

AR allows users to interact with a screen with digital overlays. This may utilise head mounted displays, or even smartphones. A popular example of AR was the Pokémon Go® mobile game. In the context of colorectal surgical training, there are a number of uses.

AR can be used to improve intra-operative outcomes. For example, AR image overlay systems superimpose three-dimensional (3D) images intra-operatively to highlight structures not ordinarily

identified, such as small gastric and colorectal tumours[16]. AR devices improve user navigation and visualisation thereby increasing the accuracy and efficiency of image-guided tumour ablations[17]. Subsequently, patients are exposed a reduced radiation dose and undergo shorter procedures than traditional CT approaches. Laser fluorescence angiography with indocyanine green (ICG) imaging represents a form of AR, overlaying a colour map to provide perfusion assessments. The technology has been reported to significantly reduce anastomotic leak rates following colorectal cancer resections[18], robotic-assisted surgery[19], and has even been used for tumour margin identification[20]. A recent systematic review concluded that ICG significantly reduces the likelihood of both anastomotic leak (ICG: 4.3%; control: 9.5%) and overall complications (ICG: 15.5%; control: 24.5%) following rectal resections[21].

With regards to training, an AR simulator, compared to cadaveric models, was shown to achieve superior laparoscopic technical skills scores; however, inferior global satisfaction scores were also reported[22]. These improvements could not be replicated for hand-assisted laparoscopy due to difficulty in replicating anatomy accurately on the simulator[23]. Additionally, an AR navigational aid improved confidence in untrained subjects when performing colonoscopy on rigid and non-rigid models of the colon; however, no beneficial effect on performance was identified[24]. Artificial intelligence (AI) has also been adapted to integrate within endoscopy, representing a form of AR. Computer aided polyp detection and diagnosis algorithms have been integrated into endoscopic stacks, thereby giving the end-user an image overlay with a diagnostic predication[25]. A multi-centre RCT has demonstrated that AI-assisted novice endoscopists achieved lower miss rates of both adenoma and polyps (18.8%; 21.2%) than a control novice group (43.7%; 35.4%)[26]. AI-assisted novices also had non-inferior adenoma miss rates compared with experts[26].

AR platforms, such as ProximieAR, also have a role in telementoring[27]. The cloud-based system allows a mentor to remotely dial into an operation and has been utilised by the Association of Coloproctology of Great Britain and Ireland (ACPGBI) for remote proctoring of colorectal surgery. Its use has not been limited to surgical experts, with reports of applications in the educational setting to teach surgical tasks on a robotic simulator to high school students and undergraduate medical students[28]. Live-streaming, recording, and commentary of procedures enabled by this technology allow for safe supervised learning.

This technology also offers a novel method of viewing 3D radiological imaging. A team from Spain demonstrated that images generated from computed tomography (CT) of 3D colon models could be visualised via an AR smartphone app to augment anatomical localisation of colonic tumours[29]. This can also be expanded to be utilised within multidisciplinary team (MDT) and radiology meetings. Moreover, 3D reconstruction has shown benefit in anatomical understanding with respect to complete mesocolic excision in right colectomies. A randomised crossover study demonstrated that 3D reconstruction was superior to systematic CT interpretation in improving vascular anatomy knowledge scores (3D group median score 8/14; CT group median score: 6/14; $p < 0.0001$)[30]. Early experiences utilising XR have also described benefits within intra-operative decision making. Understanding an absence of a high splenic flexure, and the lack of a left colic artery, changed the authors' surgical approach to an inferior mesenteric artery preserving diverticular disease resection[31]. These represent key learning opportunities for surgical trainees to understand the complexities of preoperative planning.

VIRTUAL REALITY

VR allows a user to become completely immersed within a digital world. The technology became popular with the rise of gaming headsets. The concept of a 'surgical metaverse' (i.e. a virtual world for surgical practice) has opened the door to benefits not only within surgical training, but also in peri-operative decision making[32].

Cost-effective and realistic laparoscopic VR models can be created from CT imaging[33] and magnetic resonance imaging (MRI)[34]. A virtual reality workshop, created from CT images of a physical model of the pelvic floor and anorectum, was shown to significantly improve test scores in third- and fourth-year surgical residents by 41% and 21% respectively[33]. Similarly, in a small group of surgeons (N= 10) and gastroenterologists (N= 2), VR simulator colonoscopy training significantly improved success in reaching the caecum (52% success rate compared to 19% in the control group), procedure time, and patient comfort[35]. Furthermore, a single-blinded animal-model RCT assessed laparoscopic generic skills scores and specific skills scores on scales of 7 to 35 and 8 to 40 respectively[36]. Higher laparoscopic generic skills and specific skills scores (20.1; 24.2) were observed after a single short (two hour) VR training session compared to a control group with no training (17.2; 20.2)[36]. More recently, high-fidelity VR simulators with deformable bodies and haptic feedback have been developed[37].

These benefits are not limited to endoscopy and laparoscopy; VR simulator training has been shown to improve operator performance with robotic platforms[38]. One VR system, SimNow, offers a validated approach to robotic training which correctly distinguishes between novice and more experienced surgeons[39]. Performance between competent and expert surgeons, however, could not be differentiated. The technology, therefore, could aid early years trainees in gaining exposure in robotic surgery. Multiple robotic platforms have also introduced simulation training into their bespoke industry-led curriculums, with Royal Colleges beginning to echo this[40]. Low-cost and portable versions are also in development[41,42].

Multiple studies have proven the validity of VR training in replicating in vivo colorectal surgical skills. Experienced laparoscopic colorectal surgeons were able to significantly outperform experienced colorectal surgeons who had no prior laparoscopic colectomy experience on a VR laparoscopic colectomy simulator[43]. Additionally, the GI Mentor II simulator was found to discriminate appropriately between different levels of colonoscopy expertise and offers a convincing representation of colonoscopy[44]. In a study of 105 surgical trainees, VR simulation appropriately identified improvements in laparoscopic performance[45]. Those with prior laparoscopic experience and/or video-game experience performed significantly greater overall. Moreover, VR simulation of laparoscopic sigmoid colectomy was shown to be valid measure of time, path length (i.e. the distance travelled by a surgeon's instrument), and economy of movement for medial and lateral dissection and the full procedure[46]. A representative VR model for laparoscopic appendicectomy has also been developed with construct validity in path length, idle time, and economy of movement[47].

Within the wider scope of surgical training, systematic reviews have evaluated the use of VR. One review found that for laparoscopic cholecystectomy training, VR had significantly greater Objective Structured Assessment of Technical Skills (OSATS) scores (mean difference = 6.22) and a shorter time to complete tasks (mean difference = -8.35 minutes) compared to no additional teaching[48]. However, there was no significant difference between VR and simulation training, such as laparoscopic box trainers. Another review similarly found that VR significantly outperformed video-based teaching, but that there was no significant difference between VR and box trainers[49]. Given that, in both of these reviews, benefits of VR compared to simulation-based teaching were marginally insignificant, a greater volume of research may later show that this difference becomes significant. A third review reported that VR laparoscopic training has optimal use for medical students and novice surgeons[50].

Moreover, VR may not always be an effective training modality. It has been shown to be less effective in teaching sigmoidoscopy than a traditional bedside teaching approach[51]. When participants were asked to perform the procedure on asymptomatic patients, the VR-trained group were significantly less successful in both performing retroflexion (56% vs 84%) and in reaching the splenic flexure (29% vs

72%). Additionally, there was no observed benefit from VR teaching in procedure time nor in patient satisfaction.

Due to variability in VR simulator performance between experienced endoscopists, benchmark tests were recommended to be performed by skilled operators[52]. One Delphi consensus suggests such metrics should include median expert time and economy of movement scores[53]. Subsequent RCT analysis by the same group concluded that VR training, alongside both cadaveric and cognitive training, significantly improved laparoscopic colorectal surgery performance, using two validated assessment tools, when compared to conventional residency training[54]. Intra-operative errors were suggested to not be a valid metric of VR performance for laparoscopic colectomy in isolation; instead, procedural metrics such as reduced instrument path length, successful dissection of the IMA, and accuracy of peritoneal mobilisation were more discriminatory[55].

MIXED REALITY

MR is a developing field; as such, there is limited evidence for the technology within colorectal surgical training. Multimodal MR surgical visualisation platforms have been developed from AR systems, such as the Microsoft® Hololens[56]. This device was reported to aid with anatomical visualisation during colorectal surgery, though no control group was included to allow a comparison[57]. Another study showed that use of the Microsoft HoloLens 1® as a navigation system during colectomies is sightline dependent[58]. Accuracy was optimal with users in a perpendicular sightline directly over the patient. Furthermore, during robotic transanal total mesorectal excision, MR devices can assist with identifying anatomy, and can be intuitively and comfortably used[59].

MR may also help improve trainee proficiency in wound closure. In one study, a realistic 3D model of an arm with wounds was visualised through MR glasses while the users operated tweezers and needle holders simultaneously in virtual and physical spaces[60]. The team reported that the tool had acceptable levels of usability; however, 12.9% of participants reported preferring reading text over the MR system and 38.7% felt the two methods of learning were comparable. Though MR has a number of benefits over other XR technologies (Table 1), significantly greater evidence is required to establish a role within surgical training.

DISCUSSION

XR technologies offer many advantages to conventional colorectal surgical teaching (Table 2). This includes the creation of a controlled, simulated environment whereby users can make mistakes safely and under direct supervision. Moreover, XR simulation can offer validated assessments with immediate, objective, and constructive feedback; hence, eliminating biases that may occur with subjective assessment methods. The applications of AI may enhance this further, with systematic reviews exploring their use and objectivity[61]. Robotic surgical systems have also begun to transfer aspects of bedside training to VR, with improved outcomes compared with conventional training[62]. Moreover, the translation of robotic simulation software to VR headsets has enabled remote learning of simulator exercises[63]. This may enable a faster learning curve and also mitigates the inaccessibility of the simulator when the robot is in clinical use during working hours.

XR technologies may also have applications in widening access to colorectal surgical training within remote locations and developing counties. A case involving a complex hand reconstruction, following a bomb-blast in Gaza, Palestine, was successfully assisted remotely via ProximieAR from Beirut, Lebanon[64]. Moreover, benefits of XR simulators are not limited to physicians. VR simulation outperformed CT imaging in improving patient understanding ahead of elective CRC resection[65]. VR simulation also reduced patient anxiety and improved patient understanding ahead of colonoscopy[66]. The potential patient benefits must not be understated. With improving network connections, a virtual

patient experience may replace telephone encounters, with the ability to display reports and images easily to a patient[32]. The concept of a 'meta hospital' may be facilitated by this technology; 'virtual wards' are already enabling remote NHS care for elderly patients[67].

Additionally, teaching utilising XR may be more accessible while offering a wider exposure to procedures and pathologies not normally attainable. The advancements in technology such as 5G are enabling high fidelity, real-time case observation and mentoring[68]. This also extends to the educational field, whereby master's degrees in minimally invasive surgery have been offered in a wholly virtual environment[69].

An often under-appreciated aspect of surgical training is its carbon footprint. Surgical conferences involve global travel with significant environmental consequences. It has been estimated that a shift to hybrid or online conferencing can reduce up to 94% of the carbon footprint, and up to 90% of energy use compared with in-person events[70]. Remote teaching sessions and examinations would also reduce travel made by trainees to their respective hospitals and examination centres. Furthermore, XR teaching sessions would reduce single-use plastics consumption, thereby further diminishing the carbon footprint of surgical training.

XR technologies are, however, not without their limitations. One foreseeable disadvantage to simulated learning is that XR devices are expensive to implement. There is need for a multi-factor analysis of the cost-effectiveness analysis of XR. This should include an assessment of whether the costs of implementation are offset, in part or full, by the potential financial savings of averting errors made by students in real patient situations[71]. In the United States, trainee involvement in emergency general surgery cases has been shown to be associated with prolonged operative times and a higher likelihood of adverse outcomes (including wound complications and venous thromboembolic events)[72]. However, these gains may not be transferable to the UK; the 2020 National Emergency Laparotomy Audit (NELA) concluded that trainee involvement in over 87,000 laparotomy cases was not associated with an increase in mortality nor the number of patients returned to theatre[73]. Performing teaching in a simulated environment may therefore help avoid delays to surgical cases otherwise caused by in vivo teaching, as well as having downstream cost and safety benefits.

A significant limitation of XR-based teaching is the lack of direct interaction with human patients and team members. This may worsen communication skills, empathy, and 'bedside manner', all of which are already the most common causes of patient complaints among surgeons[74]. Additionally, XR technologies (particularly MR) require significant further development. There is a lack of standardised XR training protocols and limited evidence base for its use within colorectal surgical training. Greater studies, including randomised controlled trials, investigating its educational proficiency are needed. Of note, the technology may be limited by poor internet connectivity, an issue which is notoriously rife among NHS hospitals. Further potential barriers to implementation within the NHS include a lack of facilities, infrastructure, and staffing to run teaching XR sessions.

Future applications of XR could include integration into current NHS competency-based curriculums. To achieve a surgical CCT, colorectal trainees are presently required to achieve a target number of independent procedures, including 200 colonoscopies, 80 appendicectomies, and 50 cholecystectomies. The Joint Advisory Group (JAG) currently recommends that, to achieve certification in colonoscopy, trainees should additionally attain >90% rates in unassisted caecal intubation, rectal retroversion, and polyp retrieval[75]. A competency-based method of examination is limited by potential assessor bias and a variation in procedural exposure between trainees. Allowing trainees to perform a proportion of these targets with an XR system, which can be monitored by a supervisor, could reduce trainee stress and allow for more objective assessment. Furthermore, the Objective Structured Clinical Examination

(OSCE) is utilised in postgraduate examinations for Membership of the Royal College of Surgeons (MRCS). With examiners travelling around the world to deliver this in a number of countries, XR offers a potential solution. Examiners and students could remotely "dial in", possibly with a patient or actor, to observe clinical history taking and communication skills, or to assess technical skills performed in a virtual world, such as catheterisation or suturing.

CONCLUSION

XR systems offer an array of benefits to colorectal surgical training. AR is a useful tool for simulation and may also aid in trainee involvement in preoperative planning. There is a much greater evidence base for the validity of VR in colorectal surgical training; applications include simulation for endoscopy, laparoscopy, and robotic surgery. MR is an emerging field in development which may offer a novel approach to better visualise anatomy within surgical cases.

Overall, potential advantages of XR teaching over conventional approaches include: integration with artificial intelligence; objective assessments; immediate feedback; a wider exposure to pathologies and procedures; and potential downstream safety benefits to patients and the environment. Disadvantages may include a lack of focus on patient communication skills and the lack of standardised XR training protocols. There is need for a multi-factor analysis of the cost-effectiveness of XR for surgical training. XR use within the operating theatre setting generally shows improved surgical outcomes. Exciting developments within the field and integration of XR into competency-based curriculums could offer innovative adjuncts to the training landscape.

CONTRIBUTION STATEMENT

Project commissioned by the Editor. Data acquisition by DA. Manuscript written by DA and revised by TS and GL. Figure by AR, tables by DA. Project supervised by MC.

COMPETING INTERESTS

None to declare.

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TABLES AND FIGURES

Figure 1: Extended Reality (XR) is an umbrella term for three groups of technologies. Augmented Reality (AR) shows users digitally overlayed images of the physical world. Virtual Reality (VR) immerses users in a fully virtual experience. Mixed Reality (MR) combines elements of both AR and VR, allowing users to interact with both virtual and physical worlds.

Table 1: Comparison of the advantages and disadvantages of Extended Reality (XR) technologies.

Augmented Reality (AR)	Virtual Reality (VR)	Mixed Reality (MR)
User fixed to augmented physical world only	User fixed to virtual world only	Allows user to alternate between virtual and augmented physical worlds
Limited collaboration possible	Allows for collaboration	Allows for collaboration
Can be accessed using a smartphone	Requires specialist headset and computer equipment	Requires specialist headset and computer equipment
Susceptible to device limitations	Advanced equipment capabilities	Advanced equipment capabilities
Privacy concerns of camera use	Private and controlled environment	Private and controlled environment with some privacy concerns when camera in use
Portable and easy to operate	Requires space to operate	Requires space to operate
Useful for digital overlays	Useful for visualising anatomy and practicing procedures	Useful for both digital overlays, visualising anatomy, and practicing procedures
Moderate evidence base within surgery	Highest evidence base within surgery	Limited evidence base within surgery
Less expensive to implement	Significantly expensive to implement	Moderately expensive to implement

Table 2: Summary of advantages and disadvantages offered from Extended Reality (XR)-based teaching compared to conventional in-person teaching.

Advantages	Disadvantages
Allows for a controlled environment where mistakes can be safely made	XR systems are typically expensive and a cost-effectiveness analysis is required
Immediate and constructive assessor feedback	Lack of development of communication skills with both team members and patients
Artificial Intelligence can offer objective feedback	Systems are limited by internet connectivity within hospitals
Easier to organise and facilitate teaching sessions	A limited evidence base presently
Widened exposure to pathologies and procedures	A lack of standardised XR training protocols within colorectal surgical training
Greater accessibility to robotic surgical systems	-
Teaching occurs outside of theatres, thereby preventing delays to cases	-
Widened access and inclusivity to surgical training	-
Potential downstream benefits to patient safety and surgical outcomes	-
Simulations can be shared to patients to improve pre-operative understanding and informed consent	-
May reduce climate emissions by removing the need for travel and reducing single-use plastics consumption.	-