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General Surgery 4.0 – A Systematic Review of Extended Reality Interventions in General Surgery

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Abstract

Background: Surgery is a central component of healthcare but involves significant risks, with complications occurring in 16.4% patients, accounting for 7.7% of worldwide fatalities. "Surgery 4.0" or digitisation of surgery, has introduced extended reality (XR) technology, offering opportunities to enhance peri-operative care. This study explored the current uses of XR to improve outcomes for general surgery patients.

Method: A systematic search of MEDLINE, EMBASE, and Cochrane databases was performed in August 2024 to include studies using XR for pre-operative planning, navigation or patient experience for adult patients undergoing general surgery. Data on pre-operative planning, post-operative complications, patient experience, image segmentation and study reporting were presented using a narrative approach.

Results: The search returned 966 articles. 26 studies were included featuring 1142 patients. The most investigated procedure was liver resection (n = 11, 42%), with XR interventions showing significant reductions in length of stay, blood loss, operative time and complication rates. Improved outcomes were only seen for patients undergoing liver resection. For patient experience (n = 5, 19%), XR systems were shown to significantly improve anxiety, pain and mood scores. Most studies (n = 11, 73%%) utilised manual methods for image segmentation, costing up to €650 and taking 3-6 hours per model. Reporting of the XR technology, assessment and future development was variable.

Conclusion: The benefits of XR technology to improve patient outcomes in liver surgery are emerging but are yet to materialise in other general surgical procedures. Future research should focus on automatic image segmentation to improve workflow efficiency and innovation frameworks to generate robust evidence.

Keywords

general surgery, surgical oncology, virtual reality, augmented reality, holography, clinical decision-making, systematic review

Introduction

Around 310 million major surgical procedures are performed each year worldwide.[1] Despite advances in surgery and perioperative care, surgery still involves significant risks, accounting for 7.7% of all worldwide fatalities.[2] One or more surgical complications occur in 16.4% patients, with 9% being potentially life-threatening and requiring intervention. The risk of surgical complications increases with the complexity of the procedure. For complex surgery, such as pancreatic or liver resections, the risk of surgical complications has been reported as high as 48% and 60%, respectively.[3,4] One way to reduce the rate of

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complications is to improve surgical planning. Implementation of new technologies, which enhance the review of individual patient anatomy, might improve surgical planning and improve patient outcomes. Surgical navigations systems, leveraging data from radiological imaging, could improve efficiency and safety in the operating theatre, reducing operative duration, complication rates and length of stay for patients.[5]

"Surgery 4.0" is a concept that encompasses the digitisation of surgery, including the internet of things, artificial intelligence, surgical data science, and extended reality (XR).[6] XR is an umbrella term for all devices that alter the human-computer interaction.[7] This includes virtual reality (VR), where the user sees digitally rendered images without the physical world; augmented reality (AR), involving the physical world augmented by digital information, and mixed reality (MR), which uses a mixture of methods to blend the physical and digital world. Individual patient anatomy can now be displayed in XR using medical imaging segmentation, a process involving partitioning of images into distinct regions, enabling three dimensional reconstructions.[8] XR technology has been mainly used in general surgery for surgical training and education.[9] Clinical interventions using XR for patient care are emerging, but their efficacy is largely unknown. This systematic review aims to determine the current uses of XR to improve outcomes for patients undergoing general surgery.

Methods

Study Design and Definitions

The study protocol was developed in accordance with the PRISMA and AMSTAR 2 guidelines and was prospectively registered with PROSPERO (registration number CRD42024569448).[10,11] XR interventions were defined as XR technology (VR, AR and MR) used as an intervention to influence patient outcomes in all pre-operative, intra-operative and post-operative aspects of care. The review focused on applications in general surgery, defined as gastrointestinal, endocrine, breast, trauma or organ transplantation procedures, in adult patients (aged 18 and over).

Selection Criteria

To enrich the data captured in this systematic review, all study types, excluding conference abstracts and case reports, were included. The studies included had to use XR as a patient intervention for perioperative care in adult patients undergoing a general surgical procedure. There were no time or language restrictions. Specific exclusion criteria included.

- Conference abstracts or case reports;
- Studies involving other modes of surgical visualisation technology rather than XR, such as robotic platforms or indocyanine green (ICG) fluorescence used without XR technology;
- Studies focusing on procedures not considered to be general surgery.

Systematic Literature Search

Embase (Ovid), MEDLINE (Ovid) and Cochrane Library databases were systematically searched in August 2024. All identified studies were reviewed against the inclusion and exclusion criteria to assess eligibility. Referenced studies within identified literature were accessed and considered for inclusion. Screening was performed by two independent investigators (MK and TW) and studies identified were analysed for relevance to the systematic review prior to full inspection. Any discrepancies between the independent investigators were addressed by a third senior investigator (DJ) until consensus was achieved. The search strategies used are displayed in full in Appendix S1.

Primary and Secondary Outcomes

The primary outcomes included post-operative complications (blood loss, resection margin status, operative time, complications, length of stay, mortality) to assess the impact of XR technology for pre-operative planning and surgical navigation. The secondary outcomes were collected to explore other XR interventions as part of the perioperative pathway and the current reporting of XR technologies in the literature. Secondary outcomes were grouped into.

- Surgical planning and navigation uses (pre-operative review of anatomy, anatomical structure identification);
- Patient experience (pain levels, anxiety);
- Modality of primary source imaging;
- Mode of segmentation;
- Reporting of performance, safety and preparatory steps for definitive clinical trials.

Data Extraction

Two independent investigators (MK & TW) extracted data in duplicate using a standardised data collection form. The senior author (DJ) was consulted on any discrepancies. Data were extracted on patient characteristics (age, sex, type of surgery), intervention (type of XR, perioperative stage), study characteristics (number of

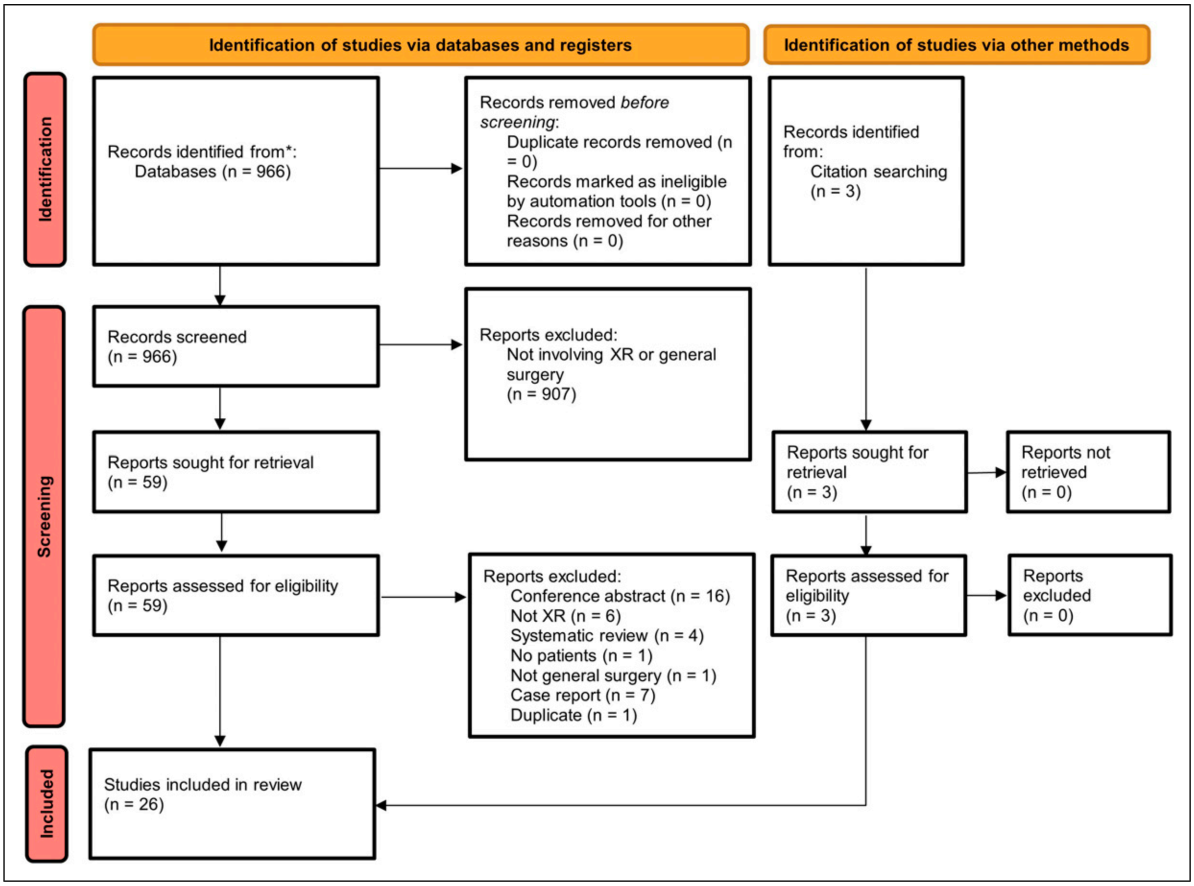

Figure 1. PRISMA flow diagram for study selection. Adapted from[10]

patients, study type, country of origin) and primary and secondary outcomes.

Data Synthesis

Included studies were tabulated and grouped according to type of general surgical procedure. Data relating to the outcomes of interest were recorded, but due to the heterogeneity amongst study types, meta-analysis of effect estimates were not performed. When applicable, treatment effects were displayed in odds ratios (ORs) or risk ratios (RRs) with 95% confidence intervals (CIs) for dichotomous data. Continuous data treatment effects were expressed as mean differences with 95% CIs. Alongside the traditional approach to reporting data, a structured narrative synthesis was conducted in line with the Guidance on the Conduct of Narrative Synthesis in Systematic Reviews from the Economic and Social Research Council.[12]

Risk of Bias

Risk of bias assessment were conducted independently by MK and TW. Any disagreements were consulted with the senior author DJ. For studies which involved a comparison group, the Cochrane's tool for assessing risk of bias was used.[13] Where applicable, the RoB-2 score was used for randomised controlled trials (RCT) and the ROBINS-I for non-randomised studies (NRS). The risk of bias was assessed as "low risk", "high risk" or "unclear risk" for each study. The results were depicted graphically using a visualisation tool by McGuinness et al[14]

Results

Included and Excluded Studies

The search strategy returned 966 articles after removing duplicate studies. Following abstract screening, 907 articles were excluded. Full-text reviews excluded 36 studies and three studies meeting inclusion criteria were identified through reference searches. The 26 included studies subsequently underwent data extraction. The selection process together with reasons for exclusion are outlined in the PRISMA flowchart in Figure 1.

Study Characteristics

The 26 included studies featured a total of 1142 patients within case series (1 study, 9 patients), NRS (19 studies,

Table 1. Study and Patient Characteristics

Ref.	Study type	Origin	n	Age	Sex (M/F%)	Surgery	XR technology	Interventional use	Risk of bias
				Patient and study characteristics					
15	NRS	China	12	54	83/77	Liver resection	AR	Intra-operative	Moderate risk
17	NRS	China	16	58	19/81	Liver resection	AR	Intra-operative	Moderate risk
26	NRS	China	85	53	82/18	Liver resection	AR	Intra-operative	Moderate risk
25	NRS	China	98	55	38/62	Liver resection	AR	Intra-operative	Moderate risk
39	NRS	China	76	52.5	84/16	Liver resection	AR	Intra-operative	Moderate risk
24	NRS	China	10	64.5	80/20	Liver resection	AR	Intra-operative	Moderate risk
18	RCT	Germany	16	70	75/25	Liver resection	VR	Intra-operative	Low risk
40	NRS	China	11	63.4	55/45	Liver resection	AR	Intra-operative	Moderate risk
41	NRS	China	48	NA	NA	Liver resection	AR	Intra-operative	Serious risk
16	NRS	France	3	60	33/67	Liver resection	AR	Intra-operative	Serious risk
34	NRS	Switzerland	2	75	50/50	Liver resection	AR	Intra-operative	Serious risk
29	RCT	Germany	62	NA	NA	Colorectal resection	VR	Patient use	Low risk
42	NRS	Japan	13	NA	NA	Colorectal resection	MR	Intra-operative	Serious risk
30	RCT	Spain	126	64	57/43	Colorectal resection	AR	Intra-operative	Low risk
21	NRS	Italy	3	NA	NA	Colorectal resection	VR	Patient use	Serious risk
22	NRS	Ireland	26	68	55/45	Colorectal resection	MR	Pre-operative	Moderate risk
19	NRS	Germany	5	66	20/80	Pancreatic resection	AR	Intra-operative	Serious risk
43	NRS	Japan	19	NA	NA	Pancreatic resection	AR	Intra-operative	Serious risk
20	NRS	Japan	7	75	43/67	Pancreatic resection	AR	Intra-operative	Serious risk
31	RCT	Iran	150	41	15/85	Cholecystectomy	VR	Patient use	Low risk
27	NRS	Japan	27	51	56/44	Cholecystectomy	AR	Intra-operative	Serious risk
28	NRS	China	34	49	25/65	Splenectomy	AR	Intra-operative	Low risk
23	Case series	South Korea	9	39	22/78	Endocrine surgery	AR	Intra-operative	Not applicable
44	NRS	Russia	8	NA	NA	Pelvic exenteration	AR	Intra-operative	Low risk
32	RCT	Turkey	225	40	59/41	Mixed abdominal	VR	Patient use	Some risks
33	RCT	Romania	51	NA	NA	Mixed abdominal	VR	Patient use	Some concerns

AR: Augmented reality; MR: Mixed reality; NRS; Non-randomised study; Randomised Controlled Trial; VR: Virtual reality.

503 patients) and RCTs (6 studies, 630 patients). RCTs were all single-centre and involved 23% of the included studies. The most investigated general surgical procedure using XR technology was liver resection in eleven studies (42%). Colorectal resection was the next most frequent in five studies (19%), followed by pancreatic resection (n = 3, 11%), cholecystectomy (n = 2, 8%), splenectomy (n = 1, 4%), pelvic exenteration (n = 1, 4%) and thyroidectomy (n = 1, 4%). Two studies involved a mixture of abdominal procedures (8%). The most frequent XR technology used was AR in 18 studies (69%), followed by VR (n = 6, 23%) and MR (n = 2, 8%). The research was primarily focused on intra-operative use (n = 21, 81%), and included interventions dedicated to patient education and recovery (n = 5, 19%). The full study characteristics are displayed in Table 1 and the main findings are depicted graphically in Figure 2.

Quality Assessment

For studies involving a comparison between two groups (case series excluded), quality assessments were performed for 25 studies (19 NRS and 6 RCTs). Using ROBINS-I, the risk of bias in NRS was assessed as "low" in two studies (n = 2/19, 11%), "moderate" in eight studies (n = 8/19, 42%) and "high" in nine studies (n = 9/19, 47%). The reasons most likely to lead to an overall "high" rating included the presence of confounders or poorly defined interventions. For RCTs, the risk of bias according to ROB-2 was assessed as "low" in four studies (n = 4/6, 67%) and "some concerns" in two studies (n = 2/6, 33%). The results are shown graphically in Appendix S2 and S3.

Operative Planning and Navigation

When examining pre-operative uses of XR, there were no studies solely dedicated to anatomical assessment or surgical planning. All studies involving the use of XR technology for pre-operative visualisation also used their technology intra-operatively. The studies reporting on operative planning and navigation are outlined in Table 2. There were no studies that investigated the use of XR to enhance MDT meetings. In liver surgery, pre-operative AR has been used to calculate predicted resected liver

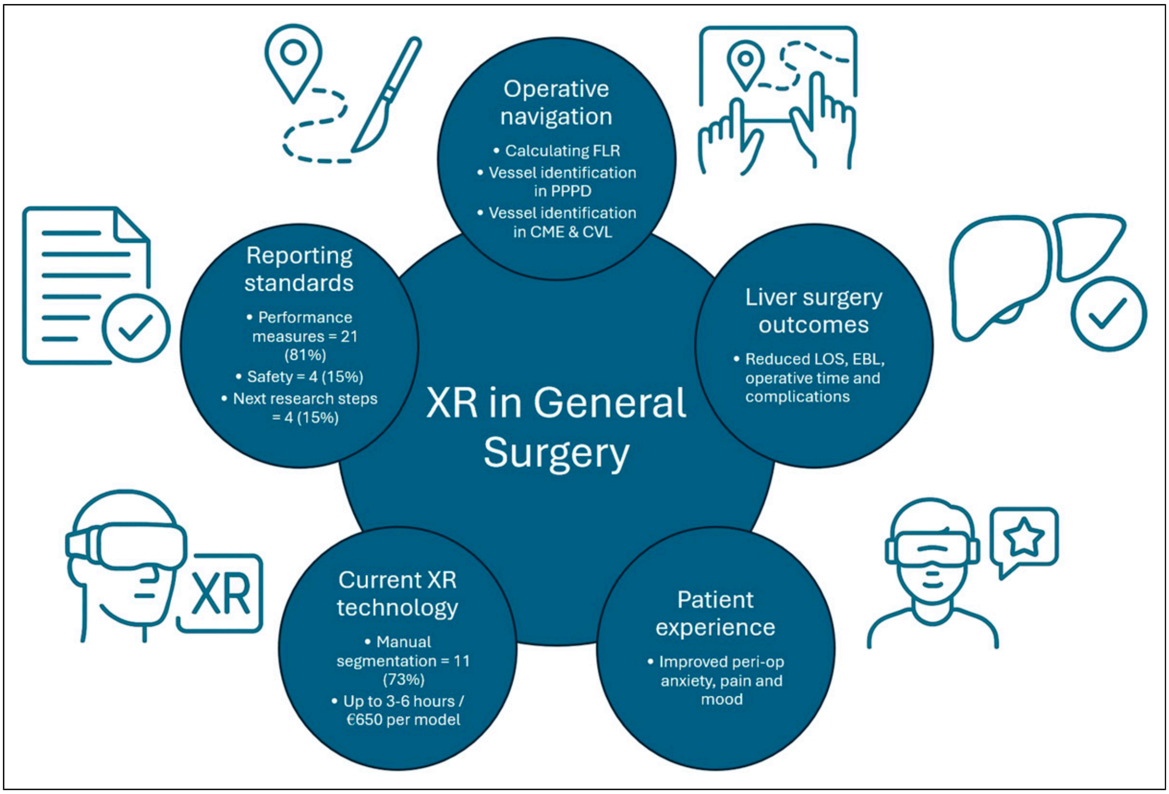

Figure 2. Graphical illustration of immersive reality technology applications and characteristics in general surgery
CME: Complete mesocolic excision; CVL: Central venous ligation; EBL: Estimated blood loss; FLR: Future liver remnant; LOS: Length of stay; PPPD: Pylorus-preserving pancreaticoduodenectomy; Peri-op: Peri-operative; R0: Resection for cure; XR: Extended reality

volume (PRLV) from preset resection plans. Zeng et al[15] performed this for laparoscopic anatomical liver resection in 12 patients, and found good agreement when compared with actual resected liver volume (ARLV) (r = 0.98, $P <$ 0.05, relative error = 8.62 +/− 6.66%). For colorectal liver metastasis (CRLMs), Ntourakis et al[16] used an AR system to locate tumours which were not identifiable post-chemotherapy using intra-operative ultrasound.

Table 2. XR Interventions for Pre-operative Planning and Surgical Navigation

Ref.	Surgery	XR technology	Pre-operative planning	Surgical navigation
15	Liver resection	AR	PRLV calculated using AR technology, good correlation with ARLV	
16	Liver resection	AR		AR used to identify CRLMs not visible using intra-operative ultrasound
17	Left hepatectomy	AR		Display of dissection plane
18	Liver resection	VR		No difference in the quotient of planned to intra-operative resection volume between VR and control groups
19	Pancreatic resection	AR		Identification of vascular structures
20	Pancreaticoduodenectomy	AR		Identification of vascular structures
21	Colorectal resection	VR	Identification of arterial anatomical abnormalities	
22	CME and CVL	AR	Identification of arteriovenous anatomical abnormalities	
23	Thyroidectomy	AR		Identification of nerve structures

ARLV: Actual resected liver volume; CME: Complete mesocolic excision; CRLM: Colorectal liver metastasis; CVL: Central venous ligation; FLR: Future liver remnant; PRLV: Predicted resected liver volume.

Using AR models created from imaging before chemotherapy, all CRLMs were identified and resected successfully. AR navigation systems were also found to be useful in another liver study, involving displays of a dissection plan for left hepatectomy.[17] Huber et al disputed these navigation findings in their RCT of 16 patients. They compared two groups (VR and control) of patients undergoing liver tumour resection. Their primary endpoint was the quotient of planned to intra-operative resection volume, which did not show any significant difference between the groups (0.94 vs 1.11, $P = 0.305$).[18]

In pancreatic surgery, XR technology has been used to identify key anatomical structures. Javaheri et al[19] used an AR system for pancreatic resection in five patients. Using AR intra-operative overlay, surgeons were able to identify all planned anatomical structures including the gastroduodenal artery, superior mesenteric artery, hepatic artery, splenic vein, inferior and superior mesenteric vein and portal vein. These structures were confirmed with intra-operative ultrasound. Onda et al[20] also found their AR system useful in seven patients undergoing pancreaticoduodenectomy. They were able to identify jejunal arteries and the inferior pancreaticoduodenal artery, which facilitated early intraoperative vascular ligation.

For colorectal procedures, Guerriero et al[21] used VR for pre-operative planning in three patients undergoing colorectal resections. The use of VR was crucial for one patient where an anatomical variant was detected with the left colic artery having an abnormally short origin from the inferior mesenteric artery, enabling the surgeon to anticipate the anomaly and execute safe surgery. Kearns et al[22] also tested their AR system for laparoscopic complete mesocolic excision and central venous ligation. Their 3-D models displayed in AR were able to detect 96% of arteriovenous variations in a cohort of 26 patients.

XR technologies have also been used for surgical planning and navigation in other general surgical procedures. An AR system was tested in the setting of robotic thyroidectomy to aid location of the recurrent laryngeal nerve.[23] In a pilot study involving six patients, all recurrent laryngeal nerves were successfully identified using an AR system with a 1.9 mm mean difference between the AR image and actual nerve position. To conclude, XR technologies have been used for pre-operative planning (such as calculating FLR) and intra-operative navigation, frequently to identify specific anatomical structures (vessels or nerves) or aid tumour identification. The current literature is limited to individual specific uses within small, early studies.

Intra-and Post-operative Outcomes

For studies which compared XR intervention and control groups, intra- and post-operative outcomes were analysed and detailed in Table 3. Liver surgery involved the most comparative studies, featuring four papers (3 NRS and 1 RCT).[18,24-26] Three studies found significantly reduced estimated blood loss (EBL), with mean differences of 100 mL ($P = 0.002$), 100 mL ($P = 0.005$), and 156.7 mL ($P < 0.001$), when AR was used for navigation in laparoscopic anatomical hepatectomy.[24-26] Zhang et al[26] also showed reduced length of stay (LOS) by 2 days ($P = 0.003$). Lou et al[24] found additional significant differences for AR navigation, including reduced operative time (mean difference 63.9 minutes, $P < 0.001$) and complication rate (31% difference, $P = 0.021$). In contrast, Huber et al[18] did not demonstrate any differences between their AR and control groups undergoing liver resection. Similar results were seen in the study by Onda which used an AR navigation system for pancreaticoduodenectomy with no differences seen when compared to their control group.[20] Laparoscopic cholecystectomy was investigated in one AR study.[27] The authors did not find any significant differences, but qualitative results suggested the technology was more beneficial for trainee grade surgeons compared to those who had completed training. Tao et al[28] also investigated an AR system, but in the setting of laparoscopic splenectomy. Their comparison revealed significantly reduced LOS (3.8 days vs 4.5 days, $P = 0.040$) and EBL (306.6 mL vs 462.6 mL, $P = 0.047$) for the AR navigation group. In summary, improved outcomes as a result of XR interventions have been displayed in liver resections. It is important to note the small sample sizes ($n < 100$) and moderate risk of bias for these studies, limiting these findings to a potential signal of clinical benefit rather than strong evidence of efficacy.

Patient Experience

A total of five studies investigated the use of XR for patient education and rehabilitation (Table 4). In colorectal surgery, Schrempf et al[29] used VR for post-operative bedside fitness exercises for patients who had undergone a colorectal resection. The results showed significantly improved mood scores (Distress thermometer difference = 0.76, $P < 0.001$) and a numerical reduction in LOS, which failed to reach statistical significance. Turrado et al[30] also focused on colorectal surgery, using VR pre-operatively for patient education and found significantly reduced pre-operative anxiety (Hospital Anxiety and Depression Scale difference = 2, $P < 0.001$) in their VR group. One study involved two intervention groups for laparoscopic cholecystectomy, using VR for either distraction or education.[31] Both VR groups showed significantly improved pre-operative anxiety (State-Trait Anxiety Inventory Scale difference = 6, $P < 0.001$) as well as post-operative pain (Visual Analogue Scale difference = 2.13, $P < 0.001$) compared to controls. Similar results were found in two studies including mixed abdominal procedures. Okutan et al compared VR exposure post-operatively for distraction

Table 3. Intra- and Post-operative Outcomes From Comparison Studies

Ref.	n	Intervention/Comparator	Surgery/Aetiology	EBL (ml)	Operative time (min)	Morbidity	Mortality	LOS (days)	R0 rate (%)	Significant findings
26	85	AR navigation system/standard lap resection	Lap anatomical hepatectomy/ primary liver cancer	AR: 200 Control: 300 $P = 0.002$	AR: 300 Control: 300	AR: 18 Control: 19 $P = 0.614$	NA	AR: 8 Control: 10 $P = 0.003$	NA	Decreased LOS and EBL in AR group
25	98	AR navigation with ICG system/standard lap resection	Lap anatomical hepatectomy/ primary liver cancer	AR: 100 Control: 200 $P = 0.005$	AR: 290 Control: 240 $P = 0.086$	AR: 14 Control: 26 $P = 0.072$	NA	AR: 7 Control: 7 $P = 0.788$	AR: 45 Control: 51 $P = 0.498$	Decreased EBL in AR
24	45	MR navigation combined with IOUS/standard lap resection	Lap anatomical hepatectomy/ primary liver cancer	MR: 102.7 Control: 259.4 $P < 0.001$	MR: 135.4 Control: 199.3 $P < 0.001$	MR: 1 Control: 7 $P = 0.021$	NA	MR: 8.4 Control: 8.9 $P > 0.05$	MR: 100 Control: 90 $P > 0.05$	Decreased EBL, complication rates and operative time in MR
18	16	VR navigation/standard resection	Lap & open liver resection/ CRLM & HCC	NA	VR: 190 Control: 185 $P > 0.05$	VR: 1 Control: 1 $P > 0.05$	NA	VR: 9 Control: 7 $P > 0.05$	VR: 100 Control: 100 $P > 0.05$	No differences
20	7	AR navigation/standard PD	PD/Pancreatic, bile duct & ampulla of Vater carcinoma	AR: 901 Control: 828 $P > 0.05$	AR: 415 Control: 425 $P > 0.05$	NA	NA	NA	NA	No differences
27	27	AR navigation/standard lap cholecystectomy	Lap cholecystectomy/ cholelithiasis & cholecystitis	AR: 0 Control: 0	AR: 74 Control: 58	AR: 0 Control: 0	AR: 0 Control: 0	NA	NA	No differences, efficacy may depend on experience
28	34	AR navigation/standard lap splenectomy	Lap splenectomy/massive splenomegaly	AR: 306.6 Control: 462.6 $P = 0.047$	AR: 178.2 Control: 166.8 $P > 0.05$	AR: 3 Control: 5 $P = 0.688$	AR: 0 Control: 0	AR: 3.8 Control: 4.5 $P = 0.04$	NA	Decreased LOS, EBL and complication rate with AR

CD: Clavien-Dindo classification grade[45]; CRLM: Colorectal liver metastasis; HCC: Hepatocellular carcinoma; ICG: Indocyanine green; IOUS: Intra-operative ultrasound; Lap: Laparoscopic; LOS: Length of stay; R0: Resection for cure; PD: Pancreaticoduodenectomy.

Table 4. XR Interventions for Patient Experience and Recovery

Ref.	n	Intervention/Comparator	Surgery/Aetiology	XR technology	Pain	Other patient outcomes	Significant findings
29	62	Daily VR bedside fitness exercises/no VR exposure	Colorectal resection/ CRC	VR		Mood VR vs control Distress thermometer difference = +0.76 ($P < 0.001$) LOS difference = 2 ($P < 0.076$)	VR improved mood, possible significant reduction in LOS
30	126	16-minute VR exposure detailing all peri-operative steps/no VR exposure	Colorectal resection/ CRC	VR		Pre-operative anxiety VR vs control HAD-D difference = −1 ($P < 0.001$) HAD-A difference = −2 ($P < 0.001$) STAI_A/S difference = −6 ($P < 0.001$) STAI_A/T difference = −6 ($P < 0.001$)	VR reduced pre-operative anxiety
31	150	10-minute VR exposure for education & 10-minute VR exposure for distraction pre- & post-surgery/no VR exposure	Lap cholecystectomy/ cholecystitis	VR	Education vs control VAS difference = 2.13 ($P < 0.001$) Distraction vs control VAS difference = 2.52 ($P < 0.001$)	Anxiety Education group vs control STAI difference = 22.8 ($P < 0.001$) Distraction group vs control STAI difference = 20.24 ($P < 0.001$)	VR improved pre-operative anxiety and post-operative pain
32	225	VR exposure post-operatively for distraction/no VR exposure	Mixed lap abdominal surgery/NA	VR	VR group vs control NRS difference = 1.03 ($P < 0.05$)	Comfort VR group vs control GCQ difference = 0.14 ($P < 0.05$)	VR improved post-operative pain and comfort
33	51	VR exposure post-operatively for distraction/no VR exposure	Major abdominal surgery/NA	VR	VR vs control VAS difference = 1.2 ($P < 0.05$)	Cognition VR vs control MMSE difference = 3.2 ($P > 0.05$)	VR improved post-operative pain

CRC: Colorectal cancer; GCQ; General comfort questionnaire; HAD-D/A: Hospital Anxiety and Depression Scale – Depression/Anxiety; Lap: Laparoscopic; LOS: Length of stay; MMSE: Mini-mental state examination; NRS: Numerical rating scale; STAI_A/S: State-Trait Anxiety Inventory Scale – State; STAI_A/T: State-Trait Anxiety Inventory Scale – Trait; VAS: Visual analogue scale.

Table 5. XR Technology Reporting

Ref.	n	Surgery	Imaging modality	Record of imaging	XR technology	Segmentation methodology	Record of performance	Record of safety	Record of steps for definitive RCT
15	12	Liver resection	CT, MRI	Not reported	AR	Manual	Correctly identified resection boundaries	Not reported	Not reported
17	16	Liver resection	Not reported	Not reported	AR	Manual	Correctly identified resection boundaries	Not reported	Not reported
26	85	Liver resection	CT	Protocol, quality control	AR	Not reported	Reported 10 minutes for setup	Not reported	Not reported
25	98	Liver resection	CT	Not reported	AR	Manual	Able to use anatomical markers for registration	Not reported	Not reported
39	76	Liver resection	CT	Protocol, quality control	AR	Manual	Able to use anatomical markers for registration	Not reported	Not reported
24	10	Liver resection	CT	Not reported	AR	Manual	Able to use anatomical markers for registration Registration error was 6.3 mm	Not reported	Not reported
18	16	Liver resection	CT, MRI	Not reported	VR	Automatic	Able to use anatomical markers for registration	Safety was demonstrated	Defined as feasibility study
40	11	Liver resection	CT	Not reported	AR	Not reported	Not reported	Safety was demonstrated	Not reported
41	48	Liver resection	Not reported	Not reported	AR	Automatic	Not reported	Not reported	Not reported
16	3	Liver resection	CT, MRI	Protocol, quality control	AR	Manual	Registration within 5-6 min All metastasis found with AR guidance	Not reported	Not reported
34	2	Liver resection	Not reported	Not reported	AR	Automatic	5 mins to register	Not reported	Not reported
29	62	Colorectal resection	NA	NA	VR	NA	Not reported	Not reported	Not reported
42	13	Colorectal resection	CT	Not reported	MR	Not reported	TLX score	Not reported	Not reported
30	126	Colorectal resection	NA	NA	AR	NA	Not reported	Not reported	Not reported
21	3	Colorectal resection	CT	Not reported	VR	Manual	Abnormal anatomy identified	Not reported	Defined as feasibility study
22	26	Colorectal resection	CT	Protocol, quality control	MR	Reported software used but unclear segmentation method	96% correct anatomy identification	Safety improved with MR	Defined as feasibility study

(continued)

Table 5. (continued)

Ref.	n	Surgery	Imaging modality	Record of imaging	XR technology	Segmentation methodology	Record of performance	Record of safety	Record of steps for definitive RCT
19	5	Pancreatic resections	CT	Not reported	AR	Manual	Correct anatomy identification	Not reported	Not reported
43	19	Pancreatic resections	CT	Not reported	AR	Not reported	Registration error was 5 mm	Not reported	Not reported
20	7	Pancreatic resections	CT	Protocol	AR	Manual, 3-6 hours per patient	Unsuccessful identification of structure 1, 6.2 mm registration accuracy	Not reported	Not reported
31	150	Cholecystectomy	NA	NA	VR	NA	Not reported	Not reported	Not reported
27	27	Cholecystectomy	CT	Not reported	AR	Manual	Image quality rates as good or very good	No safety concerns from operating time difference	Not reported
28	34	Splenectomy	CT	Protocol	AR	Not reported	Not reported	Not reported	Discussed need for large RCT
23	9	Endocrine surgery	CT	Not reported	AR	Semi-automatic	1.9 mm recognition error	Not reported	Not reported
44	8	Pelvic exenteration	CT, MRI	Not reported	AR	Manual	Concordance with scan, no surprises	Not reported	Not reported
32	225	Mixed abdominal	NA	NA	VR	NA	Not reported	Not reported	Not reported
33	51	Mixed abdominal	NA	NA	VR	NA	Not reported	Not reported	Not reported

AR: Augmented reality; CT: Computed Tomography; MR: Mixed reality; MRI: Magnetic Resonance Imaging; NRS; Non-randomised study; Randomised Controlled Trial; TLX: NASA Task Load Index score; VR: Virtual reality.

against standard of care, and showed improved post-operative pain (Visual Analogue Scale difference = 1.03, $P < 0.05$) and comfort in the VR group.[32] Droc et al[33] performed a similar study on patients undergoing major abdominal surgery and also found improved post-operative pain levels (Visual Analogue Scale difference = 1.2, $P < 0.05$) in the VR group. The use of XR has been shown to improve patient education and post-operative rehabilitation in multiple ways. The evidence presented is derived from five RCTs, with quality assessments determining three at low risk of bias and two with some concerns, strengthening the evidence of XR benefit for this part of peri-operative care.

XR Technology Reporting

Reporting of XR technology methodology, primary source imaging modality, assessment and steps for definitive research was variable (Table 5). For studies that required segmentation of imaging to produce XR displays, six (n = 6/21, 29%) did not report on their methods. Eleven (n = 11/21, 52%) studies reported manual methods of segmentation, taking up three to six hours per patient in one paper.[20] Kearns et al was the only group to discuss cost implications, stating that each virtual model cost 650 euros to produce. One (5%) study used semi-automatic systems and three (14%) used automatic systems. Out of these, two studies utilised a commercially available system[18,34] whilst the other utilised locally developed software. With regards to the origin of imaging for XR models, a majority (n = 14/21, 67%) used Computed Tomography (CT). Four studies (n = 4/21, 19%) used a combination of CT and Magnetic Resonance Imaging (MRI), whilst three (n = 3/21, 14%) did not report their source of imaging data. A minority of studies (n = 6/21, 29%) provided detail on their imaging protocols and quality assurance. 21 (81%) studies reported at least one measure of performance, whilst only four (15%) reported specifically on safety and four (15%) discussed steps for a definitive trial of their technology. In summary, the majority of the literature uses manual methods for XR image production, with limited reporting of primary image source and quality, safety outcomes and performance outcomes.

Discussion

XR systems have been found to be useful in surgical planning and navigation, particularly in identifying vascular structures and tumours in hepato-pancreato-biliary (HPB) and colorectal resections. The benefits for patient outcomes have been reported in liver surgery for primary and metastatic tumours, with reduced LOS, EBL, operative time and complication rates. These results are from small, unpowered studies; however, they provide a signal of potential benefit. Improved outcomes are yet to be defined for other general surgical procedures. For patient education and recovery, XR systems have been shown to produce significant improvements in pre-operative and post-operative anxiety, pain and mood. There are currently no studies which focus on the use of XR for patient consent or for MDT purposes within general surgery. Current XR technologies rely on primarily manual methods for imaging segmentation, which were inefficient, taking 3-6 hours per model in one study, and costly, at 650 euros per model extraction and processing. The quality of current literature is variable, with over 75% of studies at moderate or high risk of bias, and infrequent reporting of imaging source and quality, intervention safety and next steps for definitive trials and technology development. To our knowledge, this is the first systematic review to report on XR interventions in general surgery.

VR technology was first described in a science-fiction story in 1935 and has evolved considerably.[7] Current MR systems enable display of digital and real-world content through a merged reality. This facilitates their use in healthcare environments, such as the operating theatre, where space and sterility are frequent barriers for technology implementation. Despite the technological evolution, clinical uses with an evidenced benefit for patient outcomes are limited. The most recent scoping review of XR research found that much of the XR literature (40%) is aimed at surgical education rather than clinical interventions.[35] When examining studies aimed at clinical uses, literature reviews in other surgical specialities also agree that current evidence for the benefit on patient outcomes is limited.[36] The versatility of XR technology has the potential to enhance all aspects of peri-operative care, but the opportunities are yet to be developed and investigated in high-quality studies.

The strengths of this systematic review include defined inclusion criteria for XR use in general surgery. The results provide a granular description of XR utilisation as well as the benefits for patient outcomes, with significant results for patients undergoing liver surgery. The review also provides a detailed analysis of study reporting, which is variable within this emerging technological field. The quality assessments performed enable a comprehensive review of the current evidence, which is shown to be of limited quality at present. In addition, the review provides an assessment of XR technology, such as imaging source, segmentation methods, along with current limitations and the research required for wider adoption. The limitations of this study are also acknowledged. The heterogeneity of studies prohibited quantitative synthesis by meta-analysis, however, the narrative synthesis provides a meaningful analysis of research across general surgery and the XR field. The low quality of evidence found precludes recommendations for clinical practice at the current stage, but it does highlight the need for robust, high-quality research to assess the evolving XR technology.

The areas for further research in surgical XR have been highlighted. The main factor limiting widespread adoption is manual segmentation. Having experienced clinicians performing image analysis for three to six hours per patient is not feasible in a large healthcare system, such as the National Health Service (NHS). External services providing such analysis are costly, and therefore unlikely to be cost-effective. Artificial intelligence (AI) offers a possible solution for automated segmentation, enabling surgeons to view patient anatomy, operative plans, and intra-operative navigation on demand, and unlocking the potential of XR for widespread use.37 Another challenge to address will include fusion of multiple imaging modalities, as in this review 19% of studies were noted to include more than one type of imaging in their XR models. Automatic segmentation will have to account for variables, such as patient movement and timing of scans, in the image co-registration, but if solved XR models will harness the benefits of different imaging modalities. For example, CT and MRI scans can miss lesions close to the liver surface, whereas ultrasound is able to locate these, but lacks the definition to find deep small lesions in the liver parenchyma, showing that a fusion of the modalities could enhance MDT review, surgical planning and operative navigation. Another barrier to adoption involves the diversity of current XR systems. Nearly all studies involved locally developed early-stage XR systems aimed for one specific surgical application. A generic XR platform that can display multiple organ systems would be beneficial, but would require further innovation. The platforms must be versatile to cater for all surgical approaches. The included studies frequently involve an additional screen or headset to display 3D reconstructions next to laparoscopic stack systems.[22] To reduce the task load associated with new surgical tools, XR technologies must provide a seamless experience integrated within existing surgical equipment, such as laparoscopic stack systems or robotic platforms. Headsets will need to remain an option for open surgery, providing a similar experience to integrated laparoscopic or robotic solutions. In this systematic review, only four studies reported further plans for clinical trials. Ideally, XR systems should be subjected to the same prospective evaluation frameworks as other surgical technologies with minimum standards for reporting, which should include primary imaging source and quality, methods for segmentation, along with safety, efficacy, and utility.[38] XR technology has the potential to improve all aspects of peri-operative care and further studies are required to investigate its utility across the whole surgical care pathway, including multi-disciplinary decision-making and post-operative follow-up. There is scope for more research in other surgical specialties, rather than the current focus on HPB surgery. XR could also explore challenges within surgical subspecialties, such as anastomotic leak or advanced/recurrent cancer.

Conclusion

The use of XR technology has been reported for pre-operative planning, patient education, intra-operative navigation and patient rehabilitation in the field of general surgery. A signal towards improved outcomes has been shown for patients undergoing liver resections, including reduced LOS, EBL, operative time and complication rates. Similar patient benefits are yet to be documented for other general surgical procedures. The findings are limited by the quality of evidence and varied reporting standards of primary imaging source, methods of segmentation and safety. Areas for further research include AI-powered automatic image segmentation, fusion of multiple imaging modalities, interdisciplinary XR platforms, and the use of XR systems across surgical care pathways.

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Author Contributions

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The authors declared the following potential conflicts of interest with respect to the research, authorship, and/or publication of this article: Author PL has previously acted as a paid consultant for HoloCare Limited but declares no non-financial competing interests. All other authors declare no financial or non-financial competing interests.

Supplemental Material

Supplemental material is available online.

References

1. Dobson GP. Trauma of major surgery: a global problem that is not going away. *Int J Surg*. 2020;81:47-54.
2. Nepogodiev D, Martin J, Biccard B, Makupe A, Bhangu A, Nepogodiev D. Global burden of postoperative death. *Lancet*. 2019;393(10170):401.
3. Topal H, Aerts R, Laenen A, et al. Survival after minimally invasive vs open surgery for pancreatic adenocarcinoma. *JAMA Netw Open*. 2022;5(12):e2248147.
4. Egeland C, Rostved AA, Schultz NA, et al. Morbidity and mortality after liver surgery for colorectal liver metastases: a cohort study in a high-volume fast-track programme. *BMC Surg*. 2021;21(1):312.
5. *Future of Surgery Report*: Royal College of Surgeons of England; 2019 Available from: https://futureofsurgery.rcseng.ac.uk/report/Future/20of/20Surgery/20Report.pdf
6. Feussner H, Park A. Surgery 4.0: the natural culmination of the industrial revolution? *Innov Surg Sci*. 2017;2(3):105-108.
7. Andrews C, Southworth MK, Silva JNA, Silva JR. Extended reality in medical practice. *Curr Treat Options Cardiovasc Med*. 2019;21(4):18.
8. Xu Y, Quan R, Xu W, Huang Y, Chen X, Liu F. Advances in medical image segmentation: a comprehensive review of traditional, deep learning and hybrid approaches. *Bioengineering*. 2024;11(10):1034.
9. Co M, Chiu S, Billy Cheung HH. Extended reality in surgical education: a systematic review. *Surgery*. 2023;174(5):1175-1183.
10. Page MJ, McKenzie JE, Bossuyt PM, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. *Br Med J*. 2021;372:n71.
11. Shea BJ, Reeves BC, Wells G, et al. Amstar 2: a critical appraisal tool for systematic reviews that include randomised or non-randomised studies of healthcare interventions, or both. *Br Med J*. 2017;358:j4008.
12. Campbell M, Katikireddi SV, Sowden A, McKenzie JE, Thomson H. Improving conduct and reporting of narrative synthesis of quantitative data (ICONS-Quant): protocol for a mixed methods study to develop a reporting guideline. *BMJ Open*. 2018;8(2):e020064.
13. Higgins JPT, Altman DG, Gøtzsche PC, et al. Cochrane Bias Methods Group, Cochrane Statistical Methods Group. The cochrane Collaboration's tool for assessing risk of bias in randomised trials. *Br Med J*. 2011;343:d5928.
14. McGuinness LA, Higgins JPT. Risk-of-bias VISualization (robvis): an R package and shiny web app for visualizing risk-of-bias assessments. *Res Synth Methods* 2020.
15. Zeng X, Deng H, Dong Y, Hu H, Fang C, Xiang N. A pilot study of virtual liver segment projection technology in subsegment-oriented laparoscopic anatomical liver resection when indocyanine green staining fails (with video). *Surg Endosc*. 2024;38(7):4057-4066.
16. Ntourakis D, Memeo R, Soler L, Marescaux J, Mutter D, Pessaux P. Augmented reality guidance for the resection of missing colorectal liver metastases: an initial experience. *World J Surg*. 2016;40(2):419-426.
17. Deng H, Zeng X, Hu H, et al. Laparoscopic left hemihepatectomy using augmented reality navigation plus ICG fluorescence imaging for hepatolithiasis: a retrospective single-arm cohort study (with video). *Surg Endosc*. 2024;38(7):4048-4056.
18. Huber T, Tripke V, Baumgart J, et al. Computer-assisted intraoperative 3D-navigation for liver surgery: a prospective randomized-controlled pilot study. *Ann Transl Med*. 2023;11(10):346.
19. Javaheri H, Ghamarnejad O, Bade R, Lukowicz P, Karolus J, Stavrou GA. Beyond the visible: preliminary evaluation of the first wearable augmented reality assistance system for pancreatic surgery. *Int J Comput Assist Radiol Surg* 2024;20:117-129.
20. Onda S, Okamoto T, Kanehira M, et al. Identification of inferior pancreaticoduodenal artery during pancreaticoduodenectomy using augmented reality-based navigation system. *J Hepatobiliary Pancreat Sci*. 2014;21(4):281-287.
21. Guerriero L, Quero G, Diana M, et al. Virtual reality exploration and planning for precision colorectal surgery. *Dis Colon Rectum*. 2018;61(6):719-723.
22. Kearns EC, Moynihan A, Dalli J, et al. Clinical validation of 3D virtual modelling for laparoscopic complete mesocolic excision with central vascular ligation for proximal Colon cancer. *Eur J Surg Oncol*. 2024;50(11):108597.
23. Lee D, Yu HW, Kim S, et al. Vision-based tracking system for augmented reality to localize recurrent laryngeal nerve during robotic thyroid surgery. *Sci Rep*. 2020;10(1):8437.
24. Lou L, Zhang L, HL. Application effect of contrast-enhanced ultrasound combined with mixed reality technology in laparoscopic anatomical hepatectomy. *Med J Chin Peoples Lib Army*. 2023;48(10):1208.
25. Wang D, Hu H, Zhang Y, et al. Efficacy of augmented reality combined with Indocyanine green fluorescence imaging guided laparoscopic segmentectomy for hepatocellular carcinoma. *J Am Coll Surg*. 2024;238(3):321-330.
26. Zhang W, Zhu W, Yang J, et al. Augmented reality navigation for stereoscopic laparoscopic anatomical

hepatectomy of primary liver cancer: preliminary experience. *Front Oncol*. 2021;11:663236.
27. Kitagawa M, Sugimoto M, Haruta H, Umezawa A, Kurokawa Y. Intraoperative holography navigation using a mixed-reality wearable computer during laparoscopic cholecystectomy. *Surgery*. 2022;171(4):1006-1013.
28. Tao HS, Lin JY, Luo W, et al. Application of real-time augmented reality laparoscopic navigation in splenectomy for massive splenomegaly. *World J Surg*. 2021;45(7): 2108-2115.
29. Schrempf MC, Zanker J, Arndt TT, et al. Immersive virtual reality fitness games to improve recovery after colorectal surgery: a randomized single blind controlled pilot trial. *Game Health J*. 2023;12(6):450-458.
30. Turrado V, Guzman Y, Jimenez-Lillo J, et al. Exposure to virtual reality as a tool to reduce peri-operative anxiety in patients undergoing colorectal cancer surgery: a single-center prospective randomized clinical trial. *Surg Endosc*. 2021;35(7):4042-4047.
31. Abbasnia F, Aghebati N, Miri HH, Etezadpour M. Effects of patient education and distraction approaches using virtual reality on pre-operative anxiety and post-operative pain in patients undergoing laparoscopic cholecystectomy. *Pain Manag Nurs*. 2023;24(3):280-288.
32. Okutan S, Saritas S. The effect of virtual reality practice and music on patients' pain, comfort, and vital signs after laparoscopic abdominal surgery. *Surg Laparosc Endosc Percutaneous Tech*. 2024;34(3):259-267.
33. Droc G, Isac S, Nita E, et al. Postoperative cognitive impairment and pain perception after abdominal surgery-could immersive virtual reality bring more? A clinical approach. *Medicina*. 2023;59(11):2034.
34. Buchs NC, Volonte F, Pugin F, et al. Augmented environments for the targeting of hepatic lesions during image-guided robotic liver surgery. *J Surg Res*. 2013;184(2): 825-831.
35. Zhang J, Lu V, Khanduja V. The impact of extended reality on surgery: a scoping review. *Int Orthop*. 2023;47(3): 611-621.
36. Lan L, Mao RQ, Qiu RY, Kay J, de Sa D. Immersive virtual reality for patient-specific preoperative planning: a systematic review. *Surg Innov*. 2023;30(1):109-122.
37. Kowal MR, Ibrahim M, Mihaljevic AL, Kron P, Lodge P. Technological Advances in Pre-Operative Planning. *J Clin Med* 2025;14(15).
38. McCulloch P, Altman DG, Campbell WB, Flum DR, Glasziou P, Marshall JC, Nicholl J, , Balliol Collaboration. Aronson JK, Barkun JS, Blazeby JM, Boutron IC, Clavien PA, Cook JA, Ergina PL, Feldman LS, Maddern GJ, Nicholl J, Reeves BC, Seiler CM, Strasberg SM, Meakins JL, Ashby D, Black N, Bunker J, Burton M, Campbell M, Chalkidou K, Chalmers I, de Leval M, Deeks J, Ergina PL, Grant A, Gray M, Greenhalgh R, Jenicek M, Kehoe S, Lilford R, Littlejohns P, Loke Y, Madhock R, McPherson K, Meakins J, Rothwell P, Summerskill B, Taggart D, Tekkis P, Thompson M, Treasure T, Trohler U, Vandenbroucke J. No surgical innovation without evaluation: the IDEAL recommendations. *Lancet*. 2009; 374(9695):1105-1112.
39. Zhu W, Zeng X, Hu H, et al. Perioperative and disease-free survival outcomes after hepatectomy for centrally located hepatocellular carcinoma guided by augmented reality and indocyanine green fluorescence imaging: a single-center experience. *J Am Coll Surg*. 2023;236(2): 328-337.
40. Wang Z, Tao H, Wang J, et al. Laparoscopic right hemi-hepatectomy plus total caudate lobectomy for perihilar cholangiocarcinoma via anterior approach with augmented reality navigation: a feasibility study. *Surg Endosc*. 2023; 37(10):8156-8164.
41. Zhu W, Zeng XJ, Xiang N, et al. [application of augmented reality and mixed reality navigation technology in laparoscopic limited right hepatectomy]. *Zhonghua Wai Ke Za Zhi*. 2022;60(3):249-256.
42. Ryu S, Kitagawa T, Goto K, et al. Intraoperative holographic guidance using virtual reality and mixed reality technology during laparoscopic colorectal cancer surgery. *Anticancer Res*. 2022;42(10):4849-4856.
43. Okamoto T, Onda S, Yasuda J, Yanaga K, Suzuki N, Hattori A. Navigation surgery using an augmented reality for pancreatectomy. *Dig Surg*. 2015;32(2):117-123.
44. Ivanov VM, Krivtsov AM, Smirnov AY, et al. Experience in the application of augmented reality technology in the surgical treatment of patients suffering primary and recurrent pelvic tumors. *J Personalized Med*. 2023;14(1):19.
45. Dindo D, Demartines N, Clavien PA. Classification of surgical complications: a new proposal with evaluation in a cohort of 6336 patients and results of a survey. *Ann Surg*. 2004;240(2):205-213.