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Review

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Can 3D visualisation and navigation techniques improve pancreatic surgery? A systematic review

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Abstract

Pancreatic cancer, namely pancreatic ductal adenocarcinoma (PDAC), is an intractable cancer with a 5-year survival of around 7%-10%. Surgery with adjuvant chemotherapy remains the mainstay of curative treatment. The pancreas is a retroperitoneal organ that lies close to major arterial and venous structures, and it is the involvement of these structures that currently technically limits surgical resection with curative intent for pancreatic cancer. It is possible to resect venous and arterial structures involved in cancer to expand options for patients for whom surgery was previously deemed infeasible, but this is best performed in high-volume pancreatic surgery centres. Here, we explore the role that 3D visualisation and navigation surgery have in improving preoperative planning and operative execution, the role they may play in training and education and in enabling the development of novel surgical techniques in pancreatic surgery.

Keywords: 3D-visualisation, navigation surgery, cinematic rendering simulation, pancreatic surgery

INTRODUCTION

Pancreatic cancer, namely pancreatic ductal adenocarcinoma (PDAC), is an intractable cancer with a 5-year survival of around 7%-10%[1,2]. Surgery with adjuvant chemotherapy remains the mainstay of curative treatment[3]. The pancreas is a retroperitoneal organ that lies close to major arterial and venous structures, and it is the involvement of these structures that technically limits surgical resection with curative intent for PDAC. It is possible to resect venous and arterial structures involved in cancer to increase options for patients for whom surgery was previously thought to not be possible, but this is best performed in high-volume pancreatic surgery centres[4]. Resectability varies according to international classification but is currently based on anatomical definitions derived from radiographic imaging, mainly computed tomography. Unresectable pancreatic cancer, as defined by the National Comprehensive Cancer Network, encompasses tumours that exhibit distant metastasis, encasement of the superior mesenteric (SMA) or coeliac artery by more than 180 degrees, aortic encasement, or the inability to reconstruct the superior mesenteric (SMV)-portal vein (PV) complex after resection[5].

Key to successful pancreatic surgery is the delineation of relationships between vascular structures, the tumour, and the pancreas itself. This is particularly important in pancreas surgery due to the variant and aberrant anatomy common in this area. 3D visualisation and navigation surgery are techniques that have been developed mainly in diagnostic radiology technology and applied to hepatobiliary surgery, although less frequently reported in pancreatic surgery. The aim of this systematic review was to examine the role that 3D visualisation and navigation surgery have in pancreatic surgery.

METHODS

A search of MEDLINE, Embase, and Scopus databases was performed to identify relevant studies relating to the use of 3D visualisation and virtual simulation in pancreatic surgery. Search terms included: "3D visualisation", "virtual simulation", "3D reconstruction", "navigation surgery", "pancreas", "pancreas surgery", "pancreatic surgery", and "pancreatic cancer". Articles were included if they were written in English and related to pancreatic surgery only. Articles relating to hepatobiliary surgery alone and reviews were excluded. After removing duplicates, titles and abstracts were screened and full-text articles and references were reviewed by the authors. If an agreement was not reached, this was achieved by discussion.

RESULTS

The literature search identified 67 articles after removing duplicates. Following abstract screening, 51 articles were excluded and 16 were taken forward for this systematic review [Figure 1]. Twelve of the studies were from either China or Japan. Two randomised trials were identified, while the others were case series, case reports, or pilot studies. A summary of articles included in this review is provided in Table 1.

DISCUSSION

Role of 3D visualisation in preoperative planning, evaluation of resectability, and surgical training

Computed tomography (CT) and magnetic resonance (MR) based imaging modalities are the traditional methods of radiological assessment of pancreatic tumours and provide imaging that surgeons can use to guide preoperative planning, particularly with regard to relationships between key anatomical structures. These modalities are limited as they provide only a 2D representation. 3D visualisation is a process whereby 2D imaging is transformed through computer processing to provide a 3D reconstruction. Zhang *et al.* (2022) studied the role that 3D visualisation may have in changing preoperative planning in patients undergoing pancreaticoduodenectomy[6]. Patients underwent conventional CT of the abdomen in the pancreas protocol. 2D imaging was then imported into a medical image 3D visualisation system (MI-3DVS) which enabled 3D volumetric reconstructions, measurements, and rendering of discrete anatomical and pathological aspects such as tumour, lymph nodes, surrounding organs, and vasculature. Surgical planning was based on 2D and then 3D rendered imaging by the operating surgeon. Of 47 cases, surgical plans varied in 20% of cases, mainly because vascular involvement was more apparent in 3D rendered cases and this allowed the surgeon to plan for vascular resection. The surgical approach also changed after reviewing the

Table 1. Summary of studies included in this review

Title	Country	Year	Operation	Operative phase	Patients, centres	Study design	Technology	Conclusion
Theme: Cinematic rendering								
Cinematic rendering: novel tool for improving pancreatic cancer surgical planning	USA	2022	Preoperative assessment of resectability	Pre	NA, Single centre	Case series	Cinematic rendering	Cinematic rendering may improve determination of resectability, including assessment for venous resection and arterial divestment. Better appreciation of anatomical variants. Identificaiton of occult metastasis
Computer assisted surgery, preoperative planning and navigation for pancreatic cancer	Japan	2014	Pancreaticoduodenectomy	Intra	15, Single centre	Case series	CT-volume rendering imaging	Image-supported surgery to treat pancreatic cancer improves both safety and effectiveness
Theme: Navigation surgery								
Intraoperative navigation system with a multi-modality fusion of 3D virtual model and laparoscopic real-time images in laparoscopic pancreatic surgery: a preclinical study	China	2022	Preclinical model	Intra	10 surgeons	Pilot study	Navigation system with an accurate multi-modality fusion of 3D virtual model and laparoscopic real-time images	The intraoperative navigation system applied in laparoscopic pancreatic surgery clearly and correctly showed the covered anatomical structures. It has the potentiality of helping achieve a more safe and efficient laparoscopic pancreatic surgery
Identification of inferior pancreaticoduodenal artery during pancreaticoduodenectomy using augmented reality-based navigation system	Japan	2013	Pancreaticoduodenectomy	Intra	7, Single centre	Case series	AR-based NS	The AR-based NS provided precise anatomical information, which allowed the surgeons to rapidly identify and perform early ligation of IPDA in PD
Augmented reality-guided artery-first pancreatico-duodenectomy	France	2013	pancreaticoduodenectomy	Intra	1, Single centre	Case report	Augmented reality guided surgery (VR-RENDER reconstruction, VITOM exoscope)	AR is a valuable navigation tool that can enhance the ability to achieve a safe surgical resection during PD
Image-guided minimally invasive endopancreatic surgery using a computer-assisted navigation system	Switzerland	2021	Endopancreatic resection of pancreatic lesions	Intra	8, Single centre	Case series	Endopancreatic navigation using 3D reconstruction of preoperative CT	6 of 8 lesions, not visible on conventional endoscopy were resected
Novel navigation system by augmented reality technology using a tablet PC for hepatobiliary and pancreatic surgery	Japan	2018	Mixture of pancreatic and liver resections	Intra	9 (2 pancreas resections - 1 distal pancreatectomy, 1 pancreaticoduodenectomy), Single centre	Case series	Image guided navigation surgery	Improved ability to identified anatomical structures, including inferior pancreaticoduodenal artery
Navigation surgery using an augmented reality for pancreatectomy	Japan	2015	Pancreatic surgery for cancer	Intra	14 (11 pancreaticoduodenectomies, 3 distal pancreatectomies), Single centre	Case series	AR-based NS	AR-based NS contributed to accurate and effective surgical resection in pancreatectomy

Laparoscopic middle pancreatectomy under a pancreatic duct-navigation surgery	Japan	2012	Laparoscopic middle pancreatectomy	Intra	1, Single centre	Case report	Pancreatic duct-navigation surgery	Pancreatic duct-navigation surgery localized main pancreatic duct stenosis, and this method may improve minimally invasiveness and function preservation
Theme: 3D reconstruction								
Clinical Application of 3D Visualization Technology in Pancreatoduodenectomy	China	2022	Pancreaticoduodenectomy	Pre	47	Case series	3D visualisation	3D visualization technology can offer a precise and individualized surgical plan before operation, which might improve the safety of pancreatoduodenectomy, and has application value in preoperative planning
Three-Dimensional Visualization Technology Used in Pancreatic Surgery: a Valuable Tool for Surgical Trainees	China	2020	Assessment of CT scans for determining resectability for PDAC	Pre	88 residents, Single centre	Randomised controlled trial	3D reconstruction of preoperative CT	Ability to accurately stage and predict operative plan improved with 3D reconstruction
Application of three-dimensional visualization in pancreatic tumor: a pilot study	China	2017	20 malignant and 6 benign pancreatic lesions	Intra	26 patients, Single centre	Case series	3D reconstruction	3D reconstruction allows stereoscopic identification of the spatial relationships between physiologic and pathologic structures
An innovative strategy for the identification and 3D reconstruction of pancreatic cancer from CT images	Italy	2016	Preoperative assessment of pancreatic cancer	Pre	10, Single centre	Case series	3D reconstruction	In seven of ten cases, the 3D reconstruction is accepted without any modification, while in three cases, only 1.88%, 5.13%, and 5.70%, respectively, of the segmentation labels are modified, preliminary proving the high effectiveness of the tool
Three-dimensional reconstruction of the peripancreatic vascular system based on computed tomographic angiography images and its clinical application in the surgical management of pancreatic tumors	China	2014	Pancreaticoduodenectomy	Intra	89, Single centre	Randomized, parallel, single-blinded feasibility study	3D reconstruction	A peripancreatic vascular reconstruction can reveal the vascular anatomy, variations of peripancreatic vascular, and tumor-induced vascular changes; the application of the simulation surgery platform could reduce surgical trauma and decrease operative time
Short rigid scope and stereo-scope designed specifically for open abdominal navigation surgery: clinical application for hepatobiliary and pancreatic surgery	Japan	2013	Combination of HPB resections (3 distal pancreatectomies, 3 pancreaticoduodenectomies)	Intra	6, Single centre	Case series	3D reconstruction	The novel short rigid scope and stereo-scope seem to be suitable for clinical use in open abdominal navigation surgery. In hepatobiliary and pancreatic surgery, our novel system may improve the safety, accuracy and efficiency of operations
A new approach for evaluating the	China	2012	Resection for pancreatic or	Pre	80, Single centre	Case series	MI-3DVS	A new classification system is able to

resectability of pancreatic and periampullary neoplasms	periampullary tumour	reliably assess the resectability of pancreatic and periampullary tumors

AR: Augmented reality; CT: computed tomography; HPB: hepatobiliary and pancreatic surgery; IPDA: inferior pancreaticoduodenal artery; MI-3DVS: medical image three-dimensional visualization system; NS: navigation system; PDAC: pancreatic ductal adenocarcinoma.

3D visualisation in 7 cases. According to the authors, the surgical plan did not change after adjustments were made with 3D visualisation and that was the actual surgery performed.

Current definitions of resectability in PDAC relate to the involvement of the major arteries and veins: superior mesenteric artery (SMA), coeliac axis and the superior mesenteric vein (SMV) by the tumour. Determining resectability is therefore based on preoperative imaging, which is primarily via pancreas protocol CT. Of course, borderline resectable cases may undergo trial dissection, but with the increasing evidence of the benefit of neoadjuvant chemotherapy in the borderline resectable cohort, the need for accurate assessment is paramount. It has been suggested that by a standard pancreas protocol CT scan, the accuracy of determination of resectability compared to histopathological findings ranges from 73% to 83%[7,8]. This is probably limited by intra-observer variability with regard to determining vessel involvement. It has also been reported that up to 8% of pancreatectomies do not proceed beyond initial laparotomy or laparoscopy due to metastatic disease that was not previously seen on conventional imaging[9]. Fang *et al.* showed in a prospective study of 80 pancreatic and periampullary tumours, how 3D reconstruction using the MI-3DVS system changed perceived resectability in 10 of the cases, with 10 more tumours being deemed resectable when analysed using the 3D reconstructed images[10]. At operation, all tumours deemed resectable by 3D visualisation were indeed resectable. They thus claim that the sensitivity and specificity of 100% is significantly different from the 90% sensitivity and 82.5% specificity of conventional 2D computed tomography.

A novel technique of 3D reconstruction is cinematic rendering. Cinematic rendering moves beyond standard 3D reconstruction and generates life-like images from CT scans. It applies technology taken from the Pixar animation studios and provides additional accurate displays of shadows, textures, and an increased depth of field. Post-processing technology allows highly modifiable windowing so that, for example, a specific area of interest, its vascular supply, and the adjacent tissues can be delineated in more depth. This textual assessment has been evaluated in the assessment of pancreatic cysts and can be used to differentiate between solid and cystic pancreatic tumours, and the internal architecture of cystic lesions to appreciate septation and nodularity, for example. This may allow, for example, pancreatic cysts on a surveillance programme to be evaluated more clearly prior to endoscopic ultrasound assessment.

Javed *et al.* (2022) discuss the use of Cinematic rendering at the Johns Hopkins Hospital pancreas multidisciplinary clinic[11]. Cinematic rendering allows more accurate arterial assessment in borderline resectable cases, particularly of the SMA, by allowing accurate distinction between the perineural invasion of the dense perineural sheath and lymphatic channels surrounding the SMA from true tumour invasion [Figure 2][11]. They suggest that R0 resection can be achieved with perineural invasion through divestment or periadventitial dissection and the ability to determine this preoperatively is achievable through cinematic

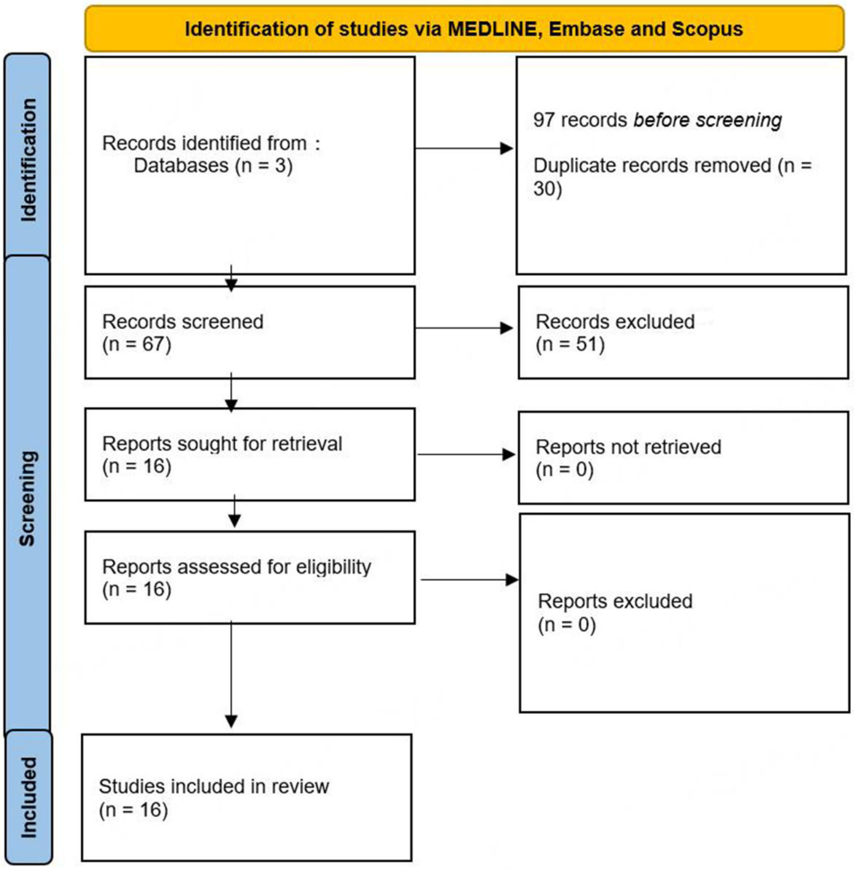

Figure 1. PRISMA flow diagram.

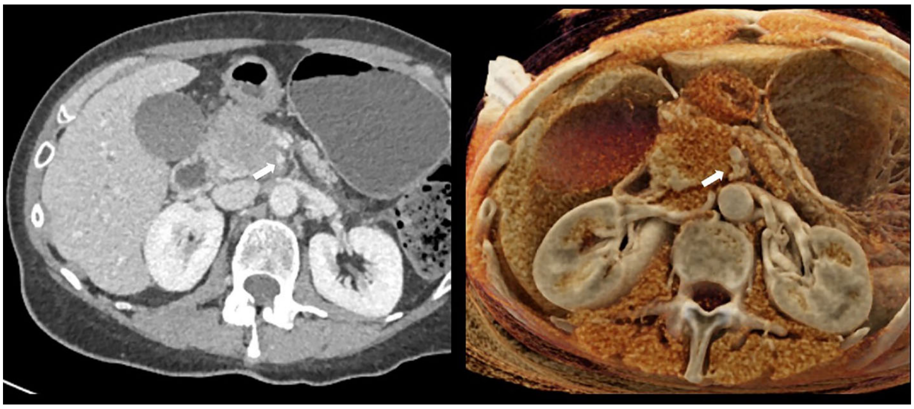

Figure 2. Cinematic rendering of a pancreas protocol CT demonstrating the ability of cinematic rendering to allow for nuanced visualization of a plane between the tumour and vessel (arrows). Figure 2 is reprinted from Current Problems in Diagnostic Radiology, 51(6), Javed AA, Young RWC, Habib JR, Kinny-Köster B, Cohen SM, Fishman EK, Wolfgang CL, Cinematic Rendering: Novel Tool for Improving Pancreatic Cancer Surgical Planning, 878-883, Copywrite (2022)m with permission from Elsevier.

rendering. The oncological benefit of this, however, remains debatable. Venous involvement again can be accurately predicted using cinematic rendering to help determine tumour adherence from true invasion. Moreover, it allows better preoperative planning as to the need for and type of venous resection and reconstruction that may be required. Finally, they suggest that occult metastasis is better appreciated on cinematic rendering imaging, as it has the ability to determine subtle liver and peritoneal metastasis from normal tissues better than both conventional CT and positron emission tomography (PET-CT).

Lin *et al.* (2018) looked at the role of 3D visualisation in residency training in pancreaticoduodenectomy[12]. The aim was to assess if 3D visualisation improved residents' ability to determine resectability using 3D visualisation imaging. Eighty-eight surgical residents underwent training on evaluating resectability using conventional 2D imaging utilising the NCCN clinical practice guidelines. They were then randomised to evaluate the same imaging in 3D or continue using the 2D images. Residents were then evaluated on two further cases and asked questions regarding recognition of anatomy, tumour staging, and surgical planning. Those residents who underwent 3D visualisation training had an improved understanding of tumour staging and spatial relationships between tumours and adjacent structures, as well as surgical planning of complex tumours.

Use of virtual simulation and augmented reality navigation for arterial assessment during pancreaticoduodenectomy

While 3D visualisation of its various forms allows better preoperative assessment, planning and assessment of resectability of pancreatic lesions, 3D visualisation techniques can be applied intraoperatively to allow augmented reality navigation-guided surgery to be a possibility. Developed over the last 20 years, its application to pancreatic surgery is relatively new, perhaps due to the ease of application to minimally invasive surgery compared to open techniques.

Marzano *et al.* (2013) describe the use of augmented reality navigation-guided surgery to improve the ability to perform the "artery first" approach to pancreaticoduodenectomy[13]. They suggest that it is important to dissect the retroperitoneal margin close to the SMA to determine resectability before commitment to formal resection. The authors describe a method where a 3D virtual anatomical model was obtained from conventional CT imaging (in this case, using VR-RENDER, IRCAD). Preoperatively, the imaging was used to plan the operation and a virtual surgical exploration was performed to delineate the tumour, the pancreas, and the vascular anatomy. Intraoperatively, the surgical field was viewed with an exoscopic camera, and the live feed was sent in real time to a computer scientist in a separate video room where the previous 3D reconstruction was superimposed onto the real-world view by using fixed landmarks such as the inferior vena cava, the left renal vein, and the aorta. This imaging was relayed to the operating theatre in real time to delineate structures, further augmented by venous structures being displayed in blue and arterial structures in red. The authors then describe how the path of the SMA could be easily identified and dissected from the surrounding tissues along the hanging plane and the hanging manoeuvre could be utilised to allow the completion of the dissection. The authors suggest that using this Augmented reality (AR)-guided navigation allows easier identification of the SMA and easier dissection in challenging situations such as obesity and when the uncinate process is close to vascular structures. They also suggest this will have an important role in the era of neoadjuvant chemotherapy for pancreatic ductal adenocarcinoma (PDAC), as local inflammatory reactions may make the assessment of vascular involvement more difficult.

Onda *et al.* (2013) used an augmented reality-navigation system to allow early identification of the inferior pancreaticoduodenal artery (IPDA) during pancreaticoduodenectomy in an attempt to minimise blood loss during the operation, which it is suggested occurs if the IPDA is divided after the efferent draining veins as this leads to congestion of the pancreatic head[14]. They studied this in a small proof of concept study of seven non-consecutive patients undergoing pancreaticoduodenectomy matched to those undergoing non-navigation surgery and compared operating time and intraoperative blood loss. Similar to the system described by Marzano *et al.*, it involved the reconstruction of 3D visualised imaging from preoperative CT scans and this was projected over the operating field intraoperatively[13]. They specifically displayed the origin of the SMA, jejunal artery and IPMA on the reconstructed images. In this case series, after determining resectability with the "artery first" approach to the SMA, they then either divided the IPDA at its origin, or if it originated from the first jejunal branch, the origin of the first jejunal artery was divided early in operation. When comparing this to matched individuals who underwent surgery without the navigation system with early division of the IPDA and those where the IPDA was not divided early, it was noted that the augmented reality system allowed easy visualisation of the IPDA; however, use of the system had no statistical impact on either operating time or intra-operative blood loss.

Abe *et al.* (2014) used image navigation surgery to improve the ability to achieve an R0 resection during pancreaticoduodenectomy for PDAC in borderline resectable cases[15]. They utilised 3D imaging reconstruction to determine the dissection margins if the tumour abutted either the SMA or the coeliac axis. They determined the "cutting line" required near the vessel that would achieve an R0 resection. This is the line at which dissection takes place and this margin is then sent for frozen section perioperatively. If this is positive, then the procedure did not proceed and the cancer was deemed inoperable.

Cinematic rendering technology could further revolutionise navigation surgery. It has been suggested that this imaging technology could be integrated with modern virtual reality methods such as Hololens (Microsoft). Similarly, integration of the technology would allow user integration of the data and allow a better understanding and appreciation of complex vascular anatomy[16].

Use of virtual simulation and augmented reality navigation to guide venous resection and reconstruction

Similar technology has been used during pancreaticoduodenectomy to guide venous resection and facilitate types of venous reconstruction. Tang *et al.* (2021) described the use of augmented reality technology in assisting the resection and reconstruction of the SMV in this situation[17]. Here, standard preoperative CT images of patients were taken with a slice thickness of 1.25 mm and this was reconstructed to 3D imaging using the Iqqa-Liver software (EDDA Technology, USA). They used less sophisticated technology than that described previously, but used printed QR codes that were placed in the operative field to represent the pre-set points at the common bile duct, pancreatic head, and tail of the pancreas. These were then used as fixed points to superimpose the 3D reconstructed images on the operative field utilising the X-Liver smartphone app (Beijing Tsinghua Changgung Hospital, Beijing, China). The AR imaging was then utilised during the procedure to determine the involvement of the SMV-PV confluence and determine the extent of the SMV, PV and SV that required resection en bloc with the tumour. They suggest this benefit of the AR-guided surgery enables surgeons to visualise key anatomical relationships ahead of the dissection of those structures and allows operative decisions to be made ahead of time. Unfortunately, in their case series, they are unable to comment on whether this improves perioperative or oncological outcomes compared with conventional surgery, but they suggest this should be the aim of larger trials to determine the overall benefit of artificial guided navigation surgery in pancreaticoduodenectomy.

Navigation systems in minimally invasive pancreatic surgery

The previous discussion has focussed on open oncological resection, mainly for borderline resectable PDAC requiring better assessment of involved arteries, better attainment of an R0 resection, or for determining the need for and reconstruction after venous involvement. Du *et al.* (2022) reported the development of an intraoperative navigation system utilising a multi-modality fusion of a 3D virtual model and laparoscopic real-time images during laparoscopic pancreatic surgery[18]. 3D virtual modelling was achieved by machine learning algorithms, including the Fisher Linear Discriminant and Graph-cut algorithms. This was then loaded to a system with inbuilt navigation software. Two cases were assessed with the model and development in preclinical tests: a laparoscopic pancreatoduodenectomy for distal cholangiocarcinoma and a laparoscopic distal pancreatosplenectomy for a tail of pancreas tumour. Analysis was of surgeon experience as well as operative time, blood loss, and transfusion requirement. They suggest that the model developed allows an ability to accurately locate the main blood vessels required to safely undertake major pancreatic surgery laparoscopically. They suggest that by overlaying the 3D reconstruction of the vessels and tumour onto the laparoscopic images in real time, it provides navigation to reduce the learning curve and allow less experienced surgeons to complete the procedure as safely and efficiently as experienced operators.

Müller *et al.* (2021) take this concept further and have evaluated computer-assisted navigation in endopancreatic surgery, such as performing pancreatic resection from inside the pancreatic duct in surgery for chronic pancreatitis as opposed to duodenum-preserving pancreatic head resection[19]. Here, a rigid endoscopy is introduced via the pancreatic papilla into the pancreatic duct. They suggest that image-guided navigation here may be useful to display critical structures relative to the view from inside the pancreatic duct, which can guide the extent of resection. The evaluation was based on an artificial pancreas silicone model in this proof-of-concept study, although this was relatively high fidelity with surrounding duodenum, SMA, SMV, and aorta. It included lesions that were not visible from inside the pancreatic duct. 3D reconstructions were then made through CT of the model and were transferred to the CAS-One navigation system (CAScination AG, Bern, Switzerland). Tracking landmarks were identified as the duodenal papilla and the aorta. The study showed that, for the first time, minimally invasive endopancreatic surgery could be combined with an image-guided, computer-assisted navigation system and that it was possible to accurately locate lesions that were invisible from the endoscopic view using the navigation system. They also found there to be minimal registration errors, i.e., the accuracy of image fusion from the virtual to the real world. They suggest this could be applied to the clinical setting and allow endopancreatic surgery to be performed instead of radical open surgery for chronic pancreatitis.

CONCLUSION

3D visualisation, cinematic rendering, and navigation surgery have a role in the preoperative evaluation of resectability of pancreatic cancer, including the evaluation of arterial and venous involvement. It has been suggested that 3D visualisation may improve the accuracy of determination of resectability, which may become more important if there is a move to neoadjuvant chemotherapy for both borderline and resectable pancreatic cancer. There is evidence that these technologies can enhance the operative performance of major pancreatic surgery and in the training of future pancreatic surgeons, especially as techniques evolve and surgery is considered for a more complex patient cohort. The role of navigation technology to augment novel surgical techniques such as endopancreatic surgery is in its infancy. Most of this evidence, however, is case series or case reports of single-centre experiences with such technology outlining its feasibility and applicability. Moreover, evidence is lacking that these technologies improve oncological and patient-centred outcomes in pancreatic surgery, and this will require further evaluation.

DECLARATIONS

Authors' contributions

Concept and design of the paper, collection of data, and authorship: Stott M, Kausar A

Availability of data and materials

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Conflicts of interest
All authors declared that there are no conflicts of interest.

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Not applicable.

Consent for publication
Not applicable.

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