Review

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The application and prospection of augmented reality in hepato-pancreato-biliary surgery

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SUMMARY Augmented Reality (AR) is one of the main forms of Extended Reality (XR) application in surgery. hepato-pancreato-biliary (HPB) surgeons could benefit from AR as an efficient tool for making surgical plans, providing intraoperative navigation, and enhancing surgical skills. The introduction of AR to HPB surgery is less than 30 years but brings profound influence. From the early days of projecting liver models on patients' surfaces for locating a better puncture point to today's assisting surgeons to perform live donor liver transplantation, a series of successful clinical practices have proved that AR can play a constructive role in HPB surgery and has great potential. Thus far, AR has been shown to increase efficiency and safety in surgical resection, and, at the same time, can improve oncological outcomes and reduce surgical risk. Although AR has presented admitted advantages in surgery, AR's application is still immature as an emerging technique and needs more exploration. In this paper, we reviewed the principles of AR and its developing history in HPB surgery, describing its significant practical applications over the past 30 years. Reviewing the past attempts of AR in HPB surgery could make HPB surgeons a better understanding of future surgery and the digital trends in medicine. The routine uses of AR in HPB surgery, as an indication of the operating room entering the new era, is coming soon.

Keywords augmented reality, HPB surgery, medical visualization, artificial intelligence

1. Introduction

Augmented Reality (AR) is a relatively new technical field that promotes the integration of real-world and virtual-world information by simulation on the basis of computer science (*1*). It can superimpose virtual content which mainly are 3-dimensional models in the real world and can be captured by human senses in the whole process, so as to achieve a sensory experience beyond reality. As opposed to showing the content simply, the objects generated by the AR system could obey the physical rules like casting the shadow and the perspective. The real environment and virtual objects coexist in the same space more naturally, which allows users to complete human-computer interaction.

AR is an important branch of Extended Reality (XR). XR is human-oriented and emphasizes Human-Computer Interaction (HCI). Depending on how virtual and reality are combined, XR can be further divided into Augment Reality (AR), Virtual Reality (VR), and Mixed Reality (MR) (*2*). AR is a combination of real-time models and actual occasions, which strengthens interaction and perception and could be seen as a complement to human information acquisition. While VR would create a new three-dimensional space that simulates all human feelings. It has three characteristics (3Rs), namely, Real-time rendering, Real space, and Real interaction. The main difference between AR and VR could be summarized simply as whether an unreal scene is established to replace the real environment. MR is more like a bridge to connect the real and the unreal. But unlike the AR would respect the objective existence, the MR would modify some components of the real scene to emphasize some specific information resource of the real world.

Although AR, VR, and MR are distinct in definition, methodology, and final effect, all these visualization technologies bring significant innovations to medicine. Especially for the surgery, XR has a series of attempts to achieve inspirational consequences. In a large-scale meta-analysis, Zhang J *et al.* included one hundred and sixty-eight studies and summarized the present status of the application of the XR to surgery (*3*). Among these research, thirty-one studies used XR as a tool for making surgical plans beforehand and had been proven to have a great advantage in identifying anatomical structures in advance. Meantime, forty-nine studies applied AR to surgery to test its safety and effect. The result showed the participation of AR could help the surgeon to avoid unintentional damage. And another interesting figure is that eleven studies found VR could release post-surgery pain reducing their need for analgesics. The rest of the studies focused on surgical skills training and medical education. By and large, AR has a wider range of utilization in the surgery itself compared to VR and MR. So, this literature review will focus on the exploration and attempts of AR in hepato-pancreato-biliary (HPB) surgery.

HPB surgery is one of the most complicated portions of abdominal surgery. Abundant blood supply increased the risk of haemorrhage. Complicated anatomical structures and variations also led to the uncertainty of the surgical treatment. So, the mortality and post-surgery complications rate of HPB surgery were high in the past. However, with the application of lots of new inventions like fluorescence-guided technology, venovenous bypass, intraoperative ultrasonic monitoring, and so forth, HPB surgery has made great strides (*4-6*). New technology allowed surgeons to explore many exclusion zones which were hard to imagine before. With accumulating experience and technological improvement, from living donor liver transplantation to laparoscopic pancreatoduodenectomy, surgical technology has no big challenge for HPB surgeons anymore (*7,8*). But in recent years, the development of HPB surgery seems to hit a bottleneck. The lack of innovation, contentment with the status quo, and the dearth of groundbreaking technology advancements are troubling HPB surgeons (*9*). In a word, the HPB surgery appeals to new elicitation. This is why the academic community of surgery was so excited when AI appeared. Surgeries require high-level observative ability and deciding ability according to actual intra-operation conditions. And AR is more suitable to deal with such an intricate task based on fact. Hence the AR is no doubt to be the linchpin to thrust further progress in surgery (*10*).

2. Technical Path for Augmented Reality

The term Augment Reality was first proposed by staff Tom Caudell and David Mizell of Boeing Co. in 1990 to describe the process of adding virtual elements made by the computer to the real world (*11*). Meantime, they also gave a detailed depiction of the features of AR: fewer rendering elements and higher requirements for registration. But it was not a new invention at that time. In fact, the history of AR is much longer than the proposal of the AR concept. The first AR system could be traced back to 1968. Ivan Sutherland, the Turing Award winner from Harvard University, developed a head-mounted display that was named after the Sword of Damokles and was considered to be the prototype of later AR (*12*). The system used an optical perspective head-mounted display with two trackers, one mechanical and the other ultrasonic. Due to the limited processing power of computers at that time, this system was hung on the ceiling above the user's head and was able to convert simple wireframed images into 3D images by a connecting rod to a helmet.

A typical AR system consists of a virtual scene generation unit, displays, and interactive devices (*13*). Among them, the virtual scene generation unit is responsible for modeling, adjusting, and managing the virtual objects; the display presents the signal after the fusion of virtual and reality; and the interactive devices realize the input and output of sensory signals and environmental control operation signals. The whole working flow is modular and cooperative (Figure 1).

In the whole process, there are three core technologies that are crucial for AR: three-dimensional (3D) registration, fused signal display, and real-time computer-human interaction.

2.1. Three-dimensional registration

The 3D registration technique is the core of AR, which involves accurately placing the rendering of virtual objects or special effects, thereby ensuring mapping consistency (*14*). The mainstream of 3D registration has 3 methods

2.1.1. The method based on computer vision

Computer vision depends on images caught by cameras. The core algorithm is divided into 2 ways: marker tracking and natural feature tracking. These detective points will be recognized and re-located in a new coordinate system so that rendering models could be placed in proper 3D locations and be reflected on the screen. This method produces exquisite scenes and needs less equipment but requires high-performance central processors and complicated computation. Prolonged processing time impedes its dexterity.

2.1.2. The method based on hardware

The method based on hardware collects information from sensors. This method has a better performance in transferring between the actual and virtual coordinate systems owing to the sensors' relatively fixed position. But it is also bedeviled by equipment accuracy and environmental intervention limiting its wider utilization.

2.1.3. Mixed Method

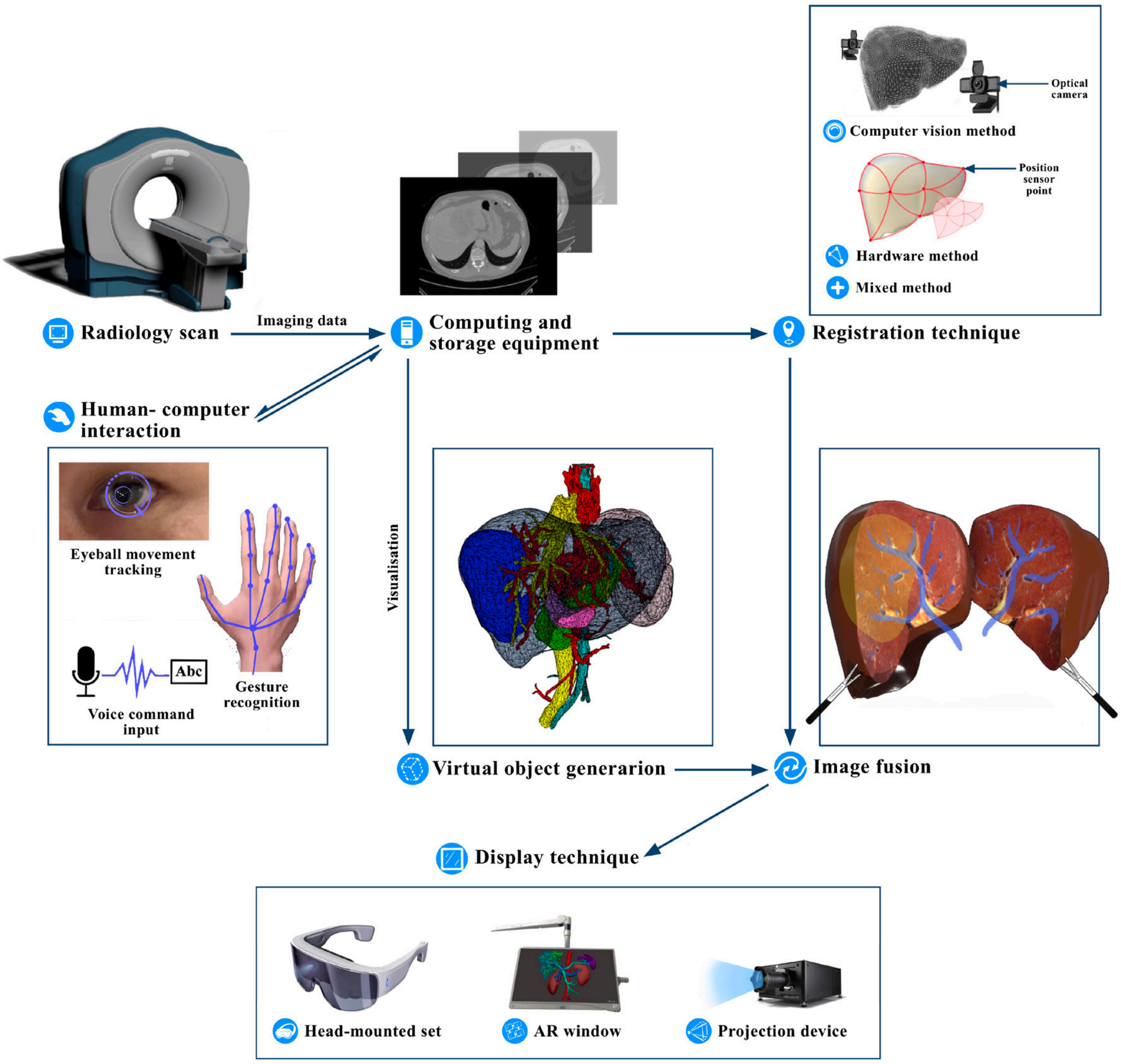

Figure 1. Augmented reality working flow chart. First, the video of the real scene is collected by the camera or sensor (Image input equipment), which is transmitted to the AR's processing unit for analysis (Computing and storage equipment). Then, combined with the data from the tracking device (Tracking technique) realizing the alignment of the coordinate system. The virtual model would appear to proper position, this step is key for the fusion calculation of the virtual and real scene (Image fusion technique). At the same time, the interactive device collects external control signals (User interaction technique). Last, the fused information will be displayed on the monitor in real-time (Display technique), namely the human field of vision.

The combination of both could increase calculating efficiency and scene quality at the same time. Many researchers devoted themselves to this kind of combination. However, good compatibility is challenging to achieve, especially when there is a difference between the camera and sensors. Consequently, it may lead to mistakes or conflicts.

2.2. Display technique

The essence of the display technique is visional representation. After registration, the position of the fused signal has been decided. So, the occlusion relationship between virtual models and real things is clear. But the experience process of AR is successive which means the display device has to be adjusted at a very high frequency according to the eye movement. Every frame needs attention on the light and shadow, distance and perspective to keep the users' optical coherence. According to the location of the equipment, all displays could be classified: the head-mounted-based display (*e.g.*, AR glasses), window-based display (*e.g.*, smartphone, tablet computer), and projection-based display (*15,16*).

2.2.1. The head-mounted-based display

The Head-Mounted Display (HMD) has a good function of information immersion, especially for wireless ones (*17*). It can enhance the user's sensory experience and free the user's hands. Besides, it also allows head movements to be tracked momently for better registration, which makes it possible to offset delays in signal transmitting and processing. But when moving the head quickly, the stability of the image is hard to be kept. This is intolerant when the AR is dealing with an emergency medical situation and may lead to disastrous results.

2.2.2. The window-based display

The AR window, including the screens of portable and fixed devices, is ubiquitous in modern life. Portable devices like smart mobile phones and tablet computers are easy to be carried with users and could be better at protecting privacy while fixed devices like public screens could realize teamwork based on the same vision. In medicine, a good application is that the tumor model could be projected to the screen of the thoracoscope according to the CT or MRI scan before the surgery, which is beneficial for delineating the area of excision for the thoracic surgical team and reducing the loss of normal tissue (*18*). However, the disadvantages are also obvious: lack of immersed feeling, lower rendering quality, and registration degree.

2.2.3. The projection-based display

Projection device could realize a large-scale scene presentation (*19*). It avoids a single focus; hence, it is more suitable when AR is applied to a large number of users at the same time. But if more interaction is needed, it will give rise to mass calculation weakening the user's experience. In addition, it is also easy to be interfered with by environmental factors like sunlight and noise.

2.3. Human-computer interaction

Human-computer interaction (HCI) is a multidisciplinary field of study focusing on the design of computer technology and, in particular, command input. It is based on reciprocal communication between users and one or several components of computer-generated environments. HCI has two principal features: the user can control the viewpoint in the AR on six degrees of freedom (Navigation) and can interact with objects within the AR (interaction) (*20*).

HCI helps virtual models to be better presented after adjusting by users discretionarily. In some cases, HCI could also do some difficult missions like working as a surgical assistant by using mechanical arms (*21*). From traditional mice and keyboards to motion tracking (*e.g.*, partial/full body, gesture), haptics (*e.g.*, force feedback), gaze tracking, and voice command, interactive technology becomes more variable. These emerging interactive modes fitting for the no-touch principle are particularly valuable for surgeries that require aseptic principles and facilitate the development of AR dramatically in surgical fields (*22*).

3. Application of AR in HPB surgery

Since the millennium, the concept of AR-aiding surgery has been wildly applied to clinical practices by more HPB surgeons, with three main applications emerging (*23*): 1 real-time intraoperative navigation, 2 preoperative simulations, and 3 surgical skills training. In addition, AR could also be used in nursing, anesthesia, and intensive care during the perioperative period (*24-26*). In fact, AR has permeated almost every part of surgery and has been transforming the traditional HPB surgical pattern fundamentally (*27*).

3.1. Real-time intraoperative navigation

The surgical navigation system refers to the organic combination of modern imaging technology, stereotactic technology, artificial intelligence, and surgeons (*28*). It makes adequate use of preoperative scan information and intraoperative findings to enable surgeons to deliver safe, precise, and minimally invasive surgical treatment.

In 1988, Marsescaux *et al.* first introduced the 3D concept to HPB, at that time 3D visualization was adopted to learn the complex liver anatomy and simulate simple liver cancer resection (*29*). Their unprecedented achievement was regarded as a major revolution in surgical practice at that time (*30*). But their attempt was limited since their visualization system only used data from the French National Library of Medicine instead of from real clinical data. One of the pioneers who adopted AR for HPB surgery navigation was Nobuhiko Hata. In 2004, his team developed an AR system called "Projected Augmented Reality" for liver surgery, which could project a 3D model of the patient's liver with a real tumor on the surface of the patient during microwave thermocoagulation, allowing surgeons to see real liver in surgery (*31*). After testing, this AR system's average registration accuracy reached 1.13 mm improving the safety of liver puncture. After that, Stüdeli *et al.* developed another AR system to improve accuracy in needle placement during percutaneous radio-frequency ablation of liver tumors also achieving an ideal result (*32*). These successful attempts made more people see a promising future of surgery aided by AR and promoted further application of AR to more complicated HPB surgery.

Then in 2009, Sugimoto *et al.* projected a virtual cholangiogram on the abdominal wall in laparoscopic cholecystectomy and highlighted hidden bile duct structures improving the surgery safety (*33*). Though this approach was only used in three cases, this was the first time that AR had been used in biliary surgery indicating that AR had officially entered the application stage in HPB surgery. However, such projection-based

AR's disadvantages were obvious: non-real-time, no interaction, and visual challenge for strong colors.

In order to achieve a true intraoperative AR, between 2005-2010, researchers explored and developed many new technologies. Hansen *et al*. presented new methods for intraoperative display of vascular structures in liver surgery reducing the visual complexity of vascular structures, and accentuating spatial relations among main branches (*34*). Shekhar *et al*. developed a live AR navigation system for laparoscopic surgery using continuous low-dose volumetric computed tomography (CT) and tested its stability through experiments upon pigs (*35*). Furthermore, Konishi *et al*. developed another navigation system based on intraoperative ultrasound (IOUS) that achieved AR registration in real-time and avoided extra radiation exposure (*36*). This system could finish scanning liver tumor mimics of pigs in 30 seconds and generate the 3D models in 3 minutes on the screen of the laparoscope. Meantime, Gavaghan *et al*. focused on developing a navigation system for open liver surgery by image overlay projection (*37*). Their extraordinary efforts laid firm ground for the application of AR to the complex HPB surgeries performed on real patients (*38*).

In 2013, Okamoto *et al*. applied AR to perform laparotomy for a patient with benign biliary stricture, a patient with gallbladder carcinoma, and a patient with hepatocellular carcinoma (HCC) (*39*). The operative procedures consisted of choledocho-jejunostomy, right hepatectomy, and microwave coagulation. The site of the tumor, preserved organs and resection aspect overlaid onto the operation field images observed by the monitors enriching the surgeons' perception. In the same year, Marzano *et al*. applied AR to a pancreatico-duodenectomy: the dissection of the superior mesenteric artery, and the hanging maneuver was performed under AR guidance along the hanging plane (*40*). A specific technician manually registered virtual and real images in real time aside. In this 360-minute surgery, AR recognized all the important vascular structures at high precision. The surgeries mentioned above were all the most difficult surgeries in abdominal surgery and AR achieved ideal effects in all of them. After then, AR began to flourish in HPB surgery.

In 2014, Kenngott *et al*. realized real-time image guidance in laparoscopic liver surgery firstly (*41*). After that, Katic *et al*. added human-computer interaction to the AR system for laparoscopic HPB surgery to filter unnecessary information display (*42*). One year later, Pessaux *et al*. first combined AR with robotic surgery to perform hepatic segmentectomy (*43,44*). The same year, Okamoto *et al*. performed pancreatectomy in five cases using AR-based navigation (*45*). Later, whether it is hilar cholangiocarcinoma resection, removal of foreign body in the pancreas, or living donor liver transplantation, AR played an increasingly complex role, and its application was becoming more mature (*46-48*). Up to now, it can be said that HPB has no restricted area for AR anymore (*49*).

3.2. Preoperative simulation

As early as 1998, the concept that AR could assist hepatic and endoscopic surgery was proposed by researchers (*29,50*). Driven by this pioneering concept, in 2003, Bornik *et al*. developed a system for liver surgery planning that enables physicians to visualize and refine segmented input liver data sets, as well as to simulate and evaluate different resections plans (*51*). The system supported surgeons in finding the optimal treatment strategy for each patient and was the first time that AR was applied to make a specific HPB surgical plan. In 2004, Reitinger *et al*. designed an AR-based system to make surgical plans for liver cancer patients (*52*). This system could provide precise position relations between the tumor and portal vein tree. They deemed that measurements based on 2D cross-sectional images were inaccurate while 3D visualization could provide more information enhancing the operational flexibility. Next, Scheuering *et al*. developed a more thorough system which consists of two parts: a preoperative planning tool for liver surgery and an intraoperative real-time visualization component (*51*). The planning tool took into account the individual anatomy of the intrahepatic vessels, determined the vascular territories, and provided methods for fast segmentation of the liver parenchyma, the intrahepatic vessels, and liver lesions. Their practical evaluation had shown a good acceptance of this system for HPB surgeons. Except for Open surgery and laparoscopic surgery, AR was also applied to ablation and interventional operation plan (*53,54*).

AR's comprehensive application in preoperative plans is not limited to make treatment strategy. AR could be also used to correct established surgical plans. Bornik *et al*. developed an AR-based liver segmentation refinement tool that aids doctors to correct inaccurate segmentations efficiently in true 3D using head-mounted displays and tracked input devices. This is of great significance for the delineation of the scope of anatomical hepatectomy because it is non-invasion and provides information beforehand so surgeons could make pointed surgical plans than depending on experience only. In addition, AR was also found to have advantages in detecting abdominal vascular variations which were hard to be reported by CT scan and CT-angiography.

Surgical planning has so far been led by the surgeon, and AR's role has been to provide information and simulation. But as AR advances, finally, surgeons may be from surgical procedure designers to approvers (*55*).

3.3. Surgical skills training

The number of patients who have undergone laparoscopic

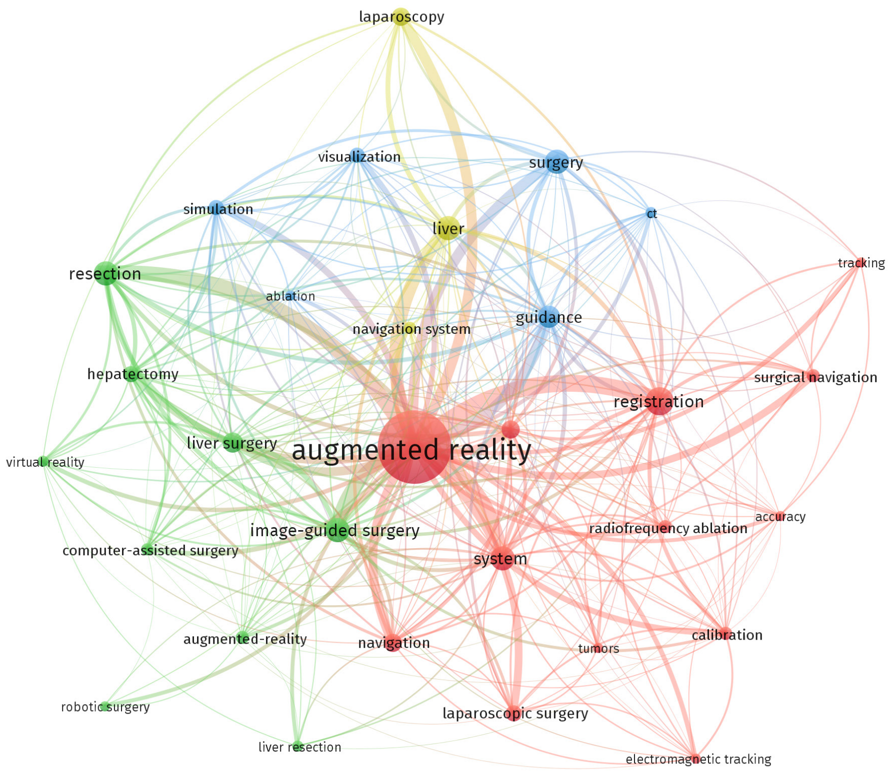

Figure 2. Net map of related literature keywords of AR application in HPB surgery.

HPB surgery has been increasing in the last 20 years. But unlike open surgery, the surgical skills of laparoscope were very hard to be practiced. Lack of sense of reality and detachment from clinical fact have always been two main learning obstacles troubling young HPB surgeons (*56*). After researchers had successfully applied of AR to anatomy education, more effort was made to develop an AR-based surgery simulation system. In 2011, Strickland developed an ex vivo simulated training model for laparoscopic liver resection (*57*). Then in 2015, Nomura *et al*. developed a VR-based training system and AR-based assessing system for laparoscopic cholecystectomy (*58*). The result showed medical students could improve their laparoscopic skills with such a form of simulator.

In addition, AR was also applied to learn complex anatomy of HPB. Viglialoro *et al*. used a well-design AR to teach the concept of Calot's triangle in laparoscopic cholecystectomy and the key points of isolation (*59*). According to the result, they believe that AR was an effective tool to learn organs with invisible vessel structure anatomy. Furthermore, Schott *et al*. appraised the effect of a VR/AR environment on multi-user liver anatomy education (*60*). The result showed that their prototype was usable, induced presence, and potentially supported the teaching of liver anatomy and surgery in the future. Interestingly, the objects who benefit from AR's education could also be the patients. Andolfi *et al*. made a 3D digital cancer model of the head of the pancreas for resident training and then 3D printed the model to carry on patient education for biliary obstruction (*61*). All these attempts expand the application field of AR and are good for cultivating new-generation HPB surgeons.

4. Conclusion and Outlook

AR technology applied in the clinical diagnosis and treatment of auxiliary has a unique advantage. The precision and safety of the AR have been testified widely. AR technology, especially for computer-combined navigation, has become a trend of medical development in the future (*62*). In 2022, the Food and Drug Administration (FDA) approved the first AI-driven AR guidance system called HOLO Portal for spinal surgery, marking the official health agency's recognition of AR-mediated surgery. Unfortunately, so far, AR products specifically suitable for HPB surgery have not yet come out, leaving a huge gap.

In the past 30 years, more than 3,000 pieces of literature about AR's application in surgery have been published, and the top three areas are neurosurgery, liver surgery, and orthopedic surgery accordingly. Obviously, HPB is undoubtedly to be the hottest spot in AR-assisted surgery research. In recent related 300 articles and reports, high-frequency keywords were analyzed (Figure 2), showing that HPB surgeons pay more attention to AR's registration and application in liver, image-guided, laparoscopic surgery.

After proving that AR was safe for HPB surgical use, many researchers began to compare its effect with traditional surgical patterns. In 2017, Diana *et al*. prospectively evaluated the identifying precision of the bile duct using AR-VR navigation and X-ray-based intraoperative cholangiography during robotic cholecystectomy for 58 patients. Ultimately, AR-VR enabled the identification of 12 anatomical variants in 8 patients, of which only 7 could be correctly reported by the radiologists (*63*). This showed that AR is a powerful complement to the surgeon's visual observation. In 2018, Cheung *et al*. compared the surgical effect between laparoscopic hepatectomy guided by AR and Indocyanine Green (ICG) fluorescence imaging and open hepatectomy for HCC (*64*). In 2023, Zhu *et al*. also made a similar effect comparison of hepatectomy for centrally located HCC guided by AR or not (*65*). Although all these studies' results were positive, it's still limited so far. High-level multicenter prospective control experiments are necessary to further evaluate the effectiveness and safety of AR in HPB surgery.

Combined with its own development trends, the hybridization of AR and other disciplines or technologies is also worthy of expecting:

i) Artificial intelligence is the star field of computer science in recent years. A typical example is the Chat Generative Pre-trained Transformer (ChatGPT) dialogue program developed by Open-AI Ltd. In addition to language models, machine learning can also help train AR systems. For the technical barriers that limit the wide application of AR in the field of surgery: action prediction and simulated elastic deformation of organs, machine learning will greatly reduce the threshold for using AR.

ii) 5th Generation Mobile Communication Technology (5G) makes short-term high-throughput information transmission possible. In fact, telemedicine that relies on 5G networks is promoting the sinking of top medical resources. The 5G network can greatly reduce the signal delay caused by huge calculations. In fact, many remote robotic surgeries have been used in medical practice. AR can better allow surgeons who are thousands of miles away to understand the details of the surgery. If it can be combined with more difficult tactile simulation, AR surgery will completely break the geographical restrictions of doctors and benefit more patients.

iii) 3D holographic projection also gives AR more possibilities. Scopis Ltd. uses a head-mounted display called HoloLens to project AR holographic images directly onto patients for surgical navigation. After testing, this 3D technology is also well-compatible with the AR system.

Despite AR has achieved series of successes in surgery, there are still some problems that need to be solved:

i) During the HPB surgery, the organ's shape and inter structure would be changing accordingly as surgeons adjust the organ's position frequently to expose a better view field. Realizing real-time reconstruction and registration of the new model is a huge challenge. It will be very low effective that surgeons have to wait for new scanning and calculating after each operation step.

ii) Visual occlusion is another problem that needs to be addressed. Especially for head-mounted sets, how to deal with optimizing their display layers? Could AR, in some extreme conditions, be a distraction for surgeons to focus on the most important part of the surgical field of vision? In other words, how to make sure the information AR presented is really constructive not a publicity stunt.

iii) Whether the over-involvement of AR will lead to the abuse of technology and make surgeons over-rely on AR slashing their creativity and could not accomplish a complex surgery when AR is not accessible? In extreme cases, the calculation and reconstruction of the model will increase the time required for preoperative preparation. For some patients who need to receive emergency surgery, is it worth spending extra time at the risk of fatal danger doing visualization instead of sending patients into operation theatre as soon as possible?

In general, from aseptic techniques, anesthesia techniques, laparoscopic techniques, and robotic techniques to today's AR, each prosperity in the surgery area have been accompanied by the application of a kind of revolutionary technology (*66*). So, it's reasonable to expect that AR will open a new chapter in the evolution of surgery. Meantime, it also needs to be recognized that, as a technology with great potential, AR is still in its infancy and requires further innovations, improvement, and grinding.

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