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Review

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Utilization of 3D printing technology in hepatopancreatobiliary surgery

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Abstract: The technology of three-dimensional (3D) printing emerged in the late 1970s and has since undergone considerable development to find numerous applications in mechanical engineering, industrial design, and biomedicine. In biomedical science, several studies have initially found that 3D printing technology can play an important role in the treatment of diseases in hepatopancreatobiliary surgery. For example, 3D printing technology has been applied to create detailed anatomical models of disease organs for preoperative personalized surgical strategies, surgical simulation, intraoperative navigation, medical training, and patient education. Moreover, cancer models have been created using 3D printing technology for the research and selection of chemotherapy drugs. With the aim to clarify the development and application of 3D printing technology in hepatopancreatobiliary surgery, we introduce seven common types of 3D printing technology and review the status of research and application of 3D printing technology in the field of hepatopancreatobiliary surgery.

Key words: 3D printing; Hepatopancreatobiliary surgery; Organ model; Cancer model

1 Introduction

Three-dimensional (3D) printing technology entails the computer-aided decomposition (CAD) of a specific shape into a series of flat slices, then using organic or inorganic materials to replicate these slices layer by layer, superimposing the accumulation, and finally forming it into a 3D solid object (Derby, 2012). In hepatopancreatobiliary surgery, 3D printing technology has shown promising applications in surgery, tissue engineering, regenerative medicine, etc. It has unique benefits and the potential to assist with surgical operations. For instance, surgeons can use computed tomography (CT) and magnetic resonance imaging (MRI) images to develop an appropriate surgical plan before surgery (Pugliese et al., 2018). In addition, 3D printing can present a detailed anatomical model of the surgical target organ. This model can provide more anatomical details and a tactile sensation of the target organ, which is superior to CT and MRI images. Surgeons can subsequently develop patient-specific surgical strategies based on this model and use it for

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surgical simulation and intraoperative navigation (Aseni et al., 2021). In tissue engineering and regenerative medicine, 3D printing technology can be utilized to create cancer models, which can simulate the survival environment of cancer cells and provide new tools for evaluating the therapeutic effects of chemotherapy drugs as well as developing new chemotherapy drugs (Wang et al., 2020).

In this review, we discuss seven common 3D printing techniques and summarize the development and research progress of 3D printing technology in hepatobiliary and pancreatic surgery (Fig. 1). We conducted a comprehensive search in the literature on 3D printing technology for hepatopancreatobiliary surgery based on PubMed. To identify relevant studies, the search strings were made up of two groups of keywords combined through the AND operator. The keywords of each group were chosen to respectively (1) define the technology of interest (3D printing technology) and (2) specify the organ of interest (the liver, gallbladder, biliary duct, and pancreas).

2 Classification of 3D printing technology

According to the standards set by the American Society for Testing and Materials International, 3D printing technologies are grouped into seven categories based on the technology and materials (Table 1) (Zhang et al., 2022). These include material extrusion (ME), vat polymerization (VP), powder bed fusion (PBF), material jetting (MJ), binder jetting (BJ), direct energy deposition (DED), and sheet lamination (SL).

2.1 Material extrusion

ME printing technology typically uses a pneumatic actuator or screw device that feeds materials through an ink cartridge into a nozzle or needle for

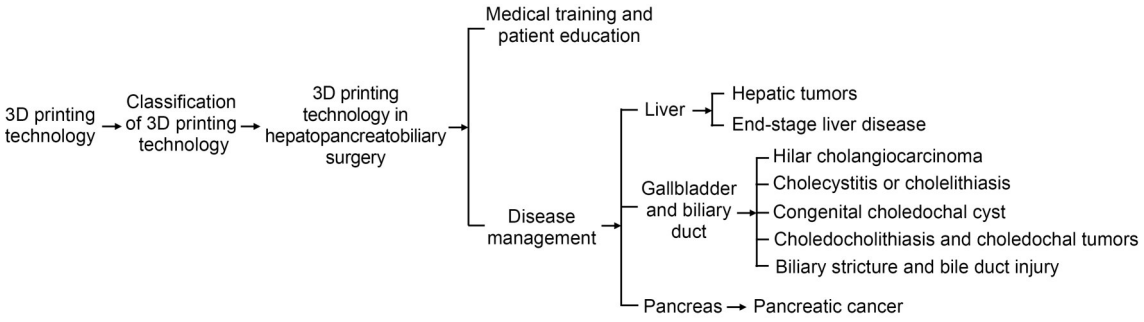

Fig. 1 Schematic view of this review article.

Table 1 Summary of different 3D printing technologies

Technology	Method	Power source	Materials	References
Material extrusion		Heat/pressure	Thermoplastic polymers	Placone and Engler, 2018; Fonseca et al., 2020
Vat polymerization	Stereolithography	Laser beam	Photopolymerizable liquid resins	Li et al., 2020; Ng et al., 2020
	Digital light processing	Light source		
	Two-photon polymerization	Femtosecond laser		
Powder bed fusion	Selective laser sintering	Laser beam	Thermoplastic polymers	Awad et al., 2020, 2021
	Selective laser melting/direct metal laser sintering	Laser beam	Metals/alloyed powders	
	Electron beam melting	Electron beam	Metals/alloyed powders	
	Multi-jet fusion	Infrared lamp	Thermoplastic polymers	
Material jetting	Continuous inkjet	Pressure	Photopolymer resins	Machekposhti et al., 2019; Fonseca et al., 2020
	Drop-on-demand	Heat/electric energy		
Binder jetting		Heat/voltage	Powder, binder	Vaz and Kumar, 2021
Direct energy deposition		Electron beam/laser/plasma arc	Metals/alloyed powders	Han et al., 2020
Sheet lamination		Laser beam	Paper, polymers, fibers, metals, ceramics	Chen JY et al., 2022

deposition, and the deposited materials are then unfolded layer by layer following a path specified by the 3D virtual model. During the printing process, multiple nozzles allow for the seamless printing of multiple materials, resulting in a more structurally integrated printed model (Placone and Engler, 2018). Currently, ME printing technology can be used to make vascular networks (Miller et al., 2012), bone models (Hung et al., 2016), and biological ovarian prostheses (Laronda et al., 2017).

2.2 Vat polymerization

VP printing is a photopolymerization technology to entrench the liquid ink layer by layer into 3D models (Li et al., 2020). This approach involves stereolithography (SLA), digital light processing (DLP), and two-photon polymerization (2PP). SLA, as the most common VP printing technology, can achieve high resolution (<100 μm) for refined structures, which mimics the microstructure of natural tissues or organs more finely (Ng et al., 2020). SLA printing technology has been used for manufacturing patient-specific implants (Wang and Sun, 2021), creating precise designs for tissue scaffolds (Guillaume et al., 2017), and fabricating organ models (Agung et al., 2021). The beam and the focal size of the micromirror determine the resolution of the DLP printing technology, which can reach the micron level (Zhu et al., 2016). DLP printing technology can be used to print various complex 3D structures, such as neuronal conduits (Li et al., 2022) and bionic vascular networks (Zhang et al., 2012). 2PP printing technology can create precise 3D microstructures with high resolution at the nanometer level and can be employed to fabricate tissue scaffolds (Jing et al., 2022).

2.3 Powder bed fusion

PBF printing technology requires the use of aggregated energy sources such as electron beams, laser beams, and infrared lamps to selectively combine powder particles from the printing platform into 3D solid structures. Depending on the energy source and the materials used, PBF is divided into four types of printing technology: selective laser sintering (SLS), selective laser melting (SLM)/direct metal laser sintering (DMLS), electron beam melting (EBM), and multi-jet fusion (MJF) (Awad et al., 2021). PBF printing has been successfully used to manufacture bone regeneration scaffolds that inhibit bacterial growth (Bassous et al., 2019), acetabular cups in hip joints (Liang et al., 2021), or maxillofacial implants (Lim et al., 2022).

2.4 Material jetting

MJ printing technology, often referred to as inkjet printing, enables the deposition of layers of finger ink in the form of small droplets on a suitable substrate. Depending on the jetting technology, MJ is classified into continuous inkjet (CIJ) printing and drop-on-demand (DOD) printing (Fonseca et al., 2020). These technologies have been used to make bones (da Conceicao Ribeiro et al., 2019), cartilage (Müller et al., 2017), and oral drugs (Musazzi et al., 2020).

2.5 Binder jetting

BJ printing technology builds 3D models by spraying binders onto a loose bed of powders through thermal or piezoelectric nozzles, allowing the layered placement of the powder to solidify, and repeating the process continuously (Vaz and Kumar, 2021). Currently, this approach can be used for pharmaceuticals (Wang et al., 2022) and manufacturing bone tissue scaffolds (Bose et al., 2021).

2.6 Direct energy deposition

DED printing technology uses laser, electron beams, or a plasma arc to melt metal in the form of metal powders or filaments during the deposition process, which are then assembled into a printed product (Han et al., 2020). The advantages of DED include the ability to create porous structures that resemble human cancellous bone while maintaining proper mechanical strength. In addition, this technology allows for the fabrication of implants using two different materials. The porous coating can be utilized to construct cementless total knee arthroplasty implants (Ryu et al., 2020).

2.7 Sheet lamination

SL printing is the process of depositing, bonding, and then cutting into the desired shape using laser beams, from paper, polymers, fibers, ceramics, or a combination of them (Chen JY et al., 2022).

3 Medical training and patient education

Unlike computer-based two-dimensional (2D) models, the 3D-printed models of organs can present

the detailed anatomy of diseased organs to surgeons and patients in a more stereoscopic and visual way. Surgeons can subsequently develop an individualized treatment plan based on the detailed anatomy. On the other hand, they can also use the detailed anatomy to explain the patient's condition to the patient and their family for a better understanding of the generation, development, and treatment of the disease and improve the patient's medical compliance. Andolfi et al. (2017) created a personalized 3D-printed model based on the CT images of a 56-year-old female patient with pancreatic head cancer. Their model allowed for a clear visualization of the relationship between cancer and blood vessels, and identified unresectable cancer, which was inconsistent with the CT images showing the junctional resectable tumor. It was demonstrated that 3D-printed models can guide surgeons in developing treatment plans, and help to discuss the condition with the patient and explain why there is no indication for surgery (Song et al., 2023). Yang TY et al. (2018) conducted a prospective study, which involved 3D printing of the livers of seven individuals with hepatic tumors. The parents were provided with information on hepatic anatomy, hepatic physiology, surgical procedures, and the associated surgical risks using CT images and 3D-printed models, and then given a questionnaire. The results showed that the parents' understanding of hepatic anatomy, hepatic physiology, surgical procedures, and associated surgical risks was significantly improved after receiving the information based on the 3D-printed models. In the treatment process, doctor–patient communication and informed consent are highly important. The above case showed that 3D-printed models can comprehensively improve patient education and contribute to helping patients agree to the doctor's treatment plan, thus reducing the difficulty of doctor–patient communication and informed consent.

The complex organ anatomy of hepatopancreatobiliary surgery poses many challenges to medical education, and 3D-printed models can greatly help to tackle them. Chedid et al. (2020) performed a randomized controlled study to investigate whether 3D-printed models can improve learners' ability to identify liver segments. The results showed that the 3D-printed model performed better than 2D images in this task. In addition, the ethical issues associated with the use of animals or cadavers for medical education are eliminated with the use of 3D-printed models. The cost of using 3D-printed models for medical education is also lower (Valls-Esteve et al., 2023). Compared to 2D images and traditional anatomical atlases, 3D-printed models not only provide haptic qualities but also help students learn the complex spatial anatomy of the liver, making it easier to understand the 3D perspective (Kong et al., 2016). Surgical training is one of the most important aspects of residency training, and 3D-printed models incorporated into such training can illustrate the detailed anatomy of organs as well as realistic haptic qualities. The ethical issues associated with the use of animals can also be avoided (Song et al., 2023; Valls-Esteve et al., 2023).

4 Disease management

4.1 Hepatic tumors

Partial hepatectomy is currently the treatment option for hepatic tumors. Adequate preoperative planning is usually required before the surgery is performed to minimize postoperative complications. Many studies have shown that 3D-printed models can realistically show the size and location of tumors. They are used for preoperative simulation, optimizing surgical plans, and providing intraoperative guidance to achieve better surgical results (Witowski et al., 2017, 2020; Wang et al., 2018; Chen et al., 2020; Huber et al., 2021; Jin et al., 2021; Lopez-Lopez et al., 2021; Rhu et al., 2021). For example, Igami et al. (2014) performed a resection of hepatic metastases in two patients with colorectal cancers based on 3D-printed hepatic models. The hepatic metastasis in one of the patients could not be detected by ultrasound because the patient was treated with chemotherapy before surgery. For this hepatic metastasis, the team determined the resection line based on the 3D-printed model. The metastasis was then accurately resected with negative surgical margins. However, creating the 3D-printed models of these two patients costs a lot of time and money, which makes this approach impossible to generalize to more patients (Wang et al., 2018). Rhu et al. (2021) printed a relatively inexpensive and time-efficient 3D model of a 50-year-old patient with hepatocellular carcinoma (HCC). The model showed a 4.7-cm-diameter HCC located in segment III and intrahepatic metastasis in segment VIII between the right portal vein, middle

hepatic vein, and right hepatic vein. It revealed that the patient's left hemi-hepatic volume ratio was about 47%, and performing an enlarged and extended left hemihepatectomy or a left trisectionectomy would leave the patient with only a residual liver of 30%–40% volume. In the context of the patient's cirrhosis, the remaining liver volume was unlikely to maintain the normal physiological requirements of the patient. Therefore, with the guidance of the 3D-printed model, the authors and their team performed a left hemihepatectomy with the preservation of middle hepatic vein and the resection of intrahepatic metastasis.

The 3D-printed models have served as a better guide not only for patients with HCC with complex tumor locations but also for patients with vascular variants. Xiang et al. (2015) reported a case of a 35-year-old patient with giant HCC in the right liver. The case was established upon enhanced CT images, which were imported into a medical imaging 3D visualization system to obtain 3D visualization models of the liver, HCC, abdominal arterial system, portal vein, and hepatic veins. The 3D visualization models showed that the patient exhibited rare abdominal vascular variants: congenital absence of the common hepatic artery, absence of the segment IV portal vein, and the origin of the variant segment IV portal vein from the right anterior portal vein, which were subsequently printed out as 3D models. The clinicians then developed a surgical plan based on these models: narrow margin right hemihepatectomy. Finally, the actual surgical operations were consistent with the developed preoperative plan (Chen et al., 2020).

With the rapid development of laparoscopic technology, laparoscopic partial hepatectomy is increasingly applied for its advantages of large surgical extent, less trauma, less bleeding, fewer postoperative complications, and a shorter hospitalization period. In laparoscopic surgery, 3D printing technology can also be used for preoperative simulation, optimizing the surgical plan and providing intraoperative guidance to achieve better surgical results. Witowski et al. (2017) printed a 3D model using enhanced CT images of a 52-year-old patient with hepatic metastases from colorectal cancer, from which the surgeons developed a surgical plan and used the model for intraoperative guidance. The patient subsequently underwent laparoscopic right hemihepatectomy with negative surgical margins (Fig. 2a). Another study used CT images of 19 patients with hepatic tumors to print out 3D models (Fig. 2b). Based on the guidance of these models, five patients changed their surgical plans. The results highlighted that 3D-printed models can help surgeons design surgical plans for complex laparoscopic hepatectomies (Witowski et al., 2020). Cheng et al. (2022) divided 54 patients into two groups: 30 patients underwent laparoscopic hepatectomy with a conventional approach and 24 patients underwent laparoscopic hepatectomy based on 3D-printed models (Fig. 2c) as well as indocyanine green fluorescence navigation. In the 3D-printed group, four patients had their surgical plans changed due to intraoperative real-time navigation and indocyanine green fluorescence. The results showed that the optimal laparoscopic surgical plan could be selected with the aid of 3D printing and indocyanine green fluorescence navigation.

Radiotherapy is one of the effective treatment options for hepatic tumors. Han et al. (2017) divided 40 patients into two groups: those in one group were treated with 3D printing-assisted ^{125}I-seed implantation and those in the other group were treated with ^{125}I-seed implantation without 3D printing assistance. The operative time, hospital stay, postoperative complications, dose distribution, and efficiency in the two groups were compared. The results indicated that the

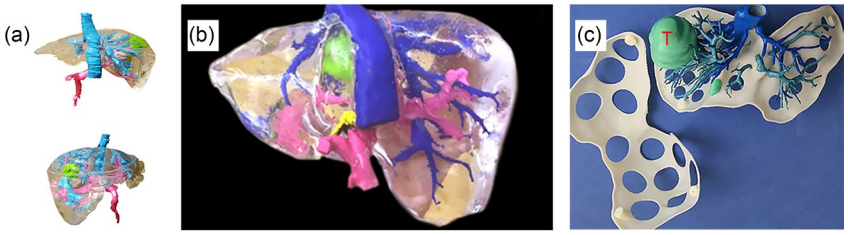

Fig. 2 Three-dimensional (3D)-printed models for hepatic tumors. (a) Liver model. Reproduced from Witowski et al. (2017) licensed under Creative Commons CC BY 4.0. (b) Liver model. Reproduced from Witowski et al. (2020) licensed under Creative Commons CC BY 4.0. (c) Liver and tumor (T) model. Reproduced from Cheng et al. (2022) licensed under Creative Commons CC BY 4.0.

application of 3D printing-assisted ^{125}I-seed implantation can shorten the operation time and optimize the dose distribution.

Xie et al. (2021) used HCC cell suspension, gelatin, and sodium alginate to configure the bioink, and then successfully constructed a 3D-bioprinted HCC model. The model provided the necessary environment of HCC, which maintained its characteristics and biological behavior during long-term culture in the model. In addition, the model was able to visualize the results of drug screening. These results confirmed that the 3D-bioprinted HCC model is reliable for in vitro culture of HCC and can be used to screen personalized drugs for patients.

4.2 End-stage liver disease

Liver transplantation is the preferred treatment option for end-stage liver disease. However, the number of donor livers cannot meet the increased demand for liver transplantation, forcing many patients to choose living-donor liver transplantation (LDLT). LDLT is the expansion of the available donor pool through partial, multisegmental grafts from a living donor. Thus, it is essential to ensure the safety of the donor and the recipient (Renz and Busuttil, 2000). Zein et al. (2013) printed 3D models of three pairs of adult donors as well as recipients, which showed the detailed location of the vessels and bile ducts, and the volume of the right or left donor liver was measured using fluid replacement. The models were also compared with the actual ones for intraoperative anatomy and hepatic volume. The results showed that the anatomy of the 3D-printed model is highly compatible with the actual intraoperative anatomy of the patient and provides more accurate volume measurements than preoperative CT images. These findings demonstrated the ability of 3D-printed models to accurately assess the hepatic volume and accurately visualize hepatic anatomy, allowing for a better preoperative plan that reduces postoperative complications. Secondly, 3D models can be used to simulate the surgery and provide intraoperative guidance during surgery to shorten the operation time and reduce the cold ischemia time of the graft, making the transplantation safer while reducing the risk of ischemia-reperfusion injury to the graft (Fang et al., 2019).

In pediatric LDLT, the key to successful LDLT fundamentally lies in graft size and graft volume mismatch can easily result in small-for-size syndrome or large-for-size syndrome. The latter is relatively common, mainly because the graft is placed in the small abdominal cavity of the child, increasing the risk of vascular complications and graft dysfunction due to the poor graft portal blood flow and graft compression after the closure of abdominal cavity (Ikegami and Maehara, 2013). Park et al. (2022) invented a less costly and more time-efficient 3D-printed model of the abdominal cavity (Fig. 3). Surgeons could do preoperative planning and simulation based on this model, which could be a good alternative to prevent large-for-size syndrome. Chen CY et al. (2022) divided 17 patients with graft-to-recipient weight ratio of ⩾4% into conventional and 3D groups to observe postoperative complications. The complication rate of blood vessels and bile ducts was the lowest among patients in the 3D group, indicating that a preoperative 3D-printed model can reduce post-transplantation complications and increase the safety of large-for-size grafts in LDLT.

The shortage of donor organs is a major challenge in the treatment of end-stage liver disease. Yang et al. (2021) prepared HepaRG cells, 0.05 g/mL gelatin, and 0.01 g/mL alginate as bioinks of the 3D-printed liver tissue model. The model had some of the functions of hepatocytes when cultured in vitro: secretion of albumin, detoxification, and synthesis of glycogen. After transplanting the liver tissue model into a fumarylacetoacetate hydrolase $(Fah)^{-/-}$ recombination-activating protein 2 $(Rag2)^{-/-}$ mouse model, the liver tissue model derived a vascular system, maintained good liver

Fig. 3 Three-dimensional (3D)-printed model of intra-abdominal cavity. Reproduced from Park et al. (2022) licensed under Creative Commons CC BY 4.0.

function, and alleviated the pre-existing liver failure. These findings demonstrate that a 3D-printed liver tissue model derived from normal hepatocytes can be used as an alternative transplant donor. However, 3D-printed liver tissue models are still at the preliminary experimental stage in animal models, and HepaRG cells cannot be used directly in humans. Therefore, it is necessary to study cell lines suitable for human use and their corresponding inks, and further experiments are needed to prove the function and safety of 3D-printed liver tissue models in humans after transplantation.

4.3 Hilar cholangiocarcinoma

Hilar cholangiocarcinoma (HC) usually has an insidious onset, rapid disease progression, and poor overall prognosis. Radical resection is the treatment of choice for HC. However, the growth site of HC is anatomically complex. Besides, Bismuth-Corlette types III and IV cancers have involved the common hepatic duct, left or right hepatic ducts, and mostly invaded the surrounding blood vessels and bile ducts. Failure to perform adequate preoperative planning can lead to increased surgical difficulties, reduced radical resection rates, and increased postoperative complications and mortality. With the guidance of 3D-printed models, clinicians can perform adequate preoperative planning to optimize surgical plans, improve surgical safety, and reduce surgical complications and mortality. For example, Zeng et al. (2020) collected preoperative CT images of ten patients with HC and printed 3D models to observe the relationship between the location of the tumor, bile ducts, and blood vessels. Vascular variants were found to exist in most patients. The 3D models were then used for preoperative planning, surgical simulation, and intraoperative navigation to guide surgical treatment. What was seen intraoperatively was consistent with the model, and all ten patients were free from bleeding, liver failure, and death in the perioperative period.

Due to the onset of HC and the lack of specificity of symptoms, most patients will have lost the opportunity for surgical treatment by the time of diagnosis. At this time, endoscopic retrograde cholangiopancreatography (ERCP) is the preferred palliative treatment modality. Yang Y et al. (2018) retrospectively analyzed the medical records of 15 patients undergoing ERCP and collected CT or magnetic resonance cholangiopancreatography (MRCP) images from patients to create 3D-printed models. These were found to be able to accurately localize the tumor and surrounding bile ducts and identify the extent of bile duct stenosis and extension. They could also be used for intraoperative navigation to reduce surgical failure rates.

4.4 Cholecystitis or cholelithiasis

The surgical indications for laparoscopic cholecystectomy are acute cholecystitis, symptomatic cholecystitis, and cholelithiasis. This type of surgery is among the most common techniques in general surgery and is necessary for hepatobiliary and pancreatic surgeons to master (Ballard et al., 2020). Casas-Murillo et al. (2021) used 3D printing to create four low-cost anatomical models for training in laparoscopic cholecystectomy, three of which had anatomical variants of the gallbladder duct. Thirteen general surgeons participated in the evaluation of the model, which was concluded to be useful for surgeon training. Moreover, many recommendations were made to make the surgery more complex.

4.5 Congenital choledochal cyst

Congenital choledochal cysts are congenital dilatations of the intrahepatic or extrahepatic bile ducts in single or multiple patterns, which are relatively common in Asian countries and are usually diagnosed in childhood. Complete resection of the cystic lesion is necessary because of the high rate of successive biliary tract cancer (ten Hove et al., 2018). Allan et al. (2019) collected CT images of a patient with a congenital common bile duct cyst and printed its 3D model, which replicated the anatomy of the bile duct and cyst. Burdall et al. (2016) constructed a model of laparoscopic common bile duct surgery for the treatment of common bile duct cysts. Studies are increasingly focusing on the role of 3D-printed models in choledochal cyst surgery, while the next important step is to validate the value of 3D-printed models in preoperative simulation and surgical simulation.

4.6 Choledocholithiasis and choledochal tumors

Bati et al. (2020) printed 3D pancreaticobiliary duct models that showed the normal anatomy of the intrahepatic bile duct, cystic duct, and bile duct. These models could overcome the limitations of conventional

MRCP images and provide a better understanding of the pathological anatomy of dilated pancreaticobiliary ducts. Preoperative planning and surgical simulation could be performed for diseases such as choledocholithiasis and choledochal tumors to ensure the safety of surgery and reduce postoperative complications.

4.7 Biliary stricture and bile duct injury

Kim et al. (2022) fabricated novel 3D-printed biodegradable stents (Fig. 4) using polycaprolactone and barium sulfate, and surgically placed them into the common bile duct of domestic pigs. The results showed that the 3D-bioprinted biodegradable stents may be used to prevent postoperative bile duct strictures. Liu et al. (2021) fabricated a dual-layer cell-laden scaffold by 3D printing with an inner layer of bone marrow mesenchymal stem cells (BMSCs) and an outer layer of gelatin methacrylate (GelMA)/polyethylene glycol diacrylate. The inner and outer bioinks ensured that the scaffold achieved good mechanical properties and cell viability. Therefore, the scaffold could be used for nerve regeneration and bile duct injury reconstruction.

4.8 Pancreatic cancer

Pancreatic cancer is a highly aggressive malignant tumor with sudden onset, difficult early diagnosis, rapid progression, and poor prognosis. The five-year survival rate of pancreatic cancer patients is ⩽10% (Siegel et al., 2021). The preferred treatment for pancreatic cancer is pancreatic surgery, such as pancreaticoduodenectomy. However, this type of pancreatic surgery is technically difficult and involves the complex vascularity of surrounding organs, as well as the need to determine whether the tumor invades surrounding vessels and tissues and the extent of invasion. Therefore, it is crucial to have preoperative information about the cancer location, size, and relationship with surrounding organs and blood vessels. The 3D-printed models can help elucidate the relationship between normal and cancer tissues, accurately formulate surgical plans, simulate surgical procedures, and provide intraoperative navigation. They can be used to quickly determine the extent of resection and surgical path, clearly distinguish the boundary between cancer and normal tissues, shorten the operation time, and reduce the risks of surgery and postoperative complications. Mahmoud and Bennett (2015) fabricated 3D-printed color models of pancreaticoduodenectomy specimens, which could clearly show the anatomical relationship between cancer tissue and normal tissue. Sampogna et al. (2017) constructed 3D-printed models of patients undergoing pancreatic surgery, which could be utilized for preoperative planning, preoperative simulation, and intraoperative guidance.

Unfortunately, only 10%–20% of pancreatic cancer patients have access to surgery. For most patients with unresectable advanced cancer and metastatic disease, chemotherapy and radiotherapy are the common treatment options. ^{125}I-seed implantation therapy is a safe and effective alternative therapy for the treatment of advanced pancreatic cancer. Twenty-five patients with inoperable advanced pancreatic cancer were subjected to ^{125}I-seed implantation therapy by Huang et al. (2018). One group received 3D printing assistance and the other group did not. The results showed that 3D printing is a safe and effective guidance tool for

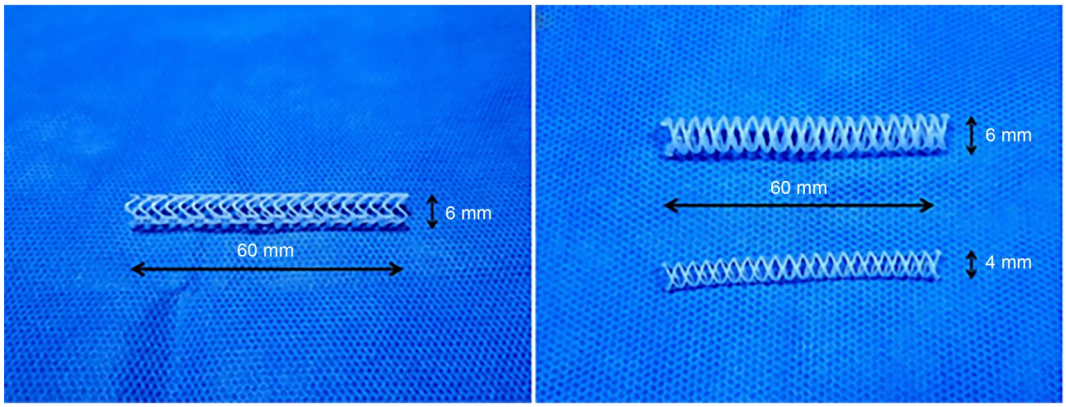

Fig. 4 Three-dimensional (3D)-printed polycaprolactone biliary stents. Reproduced from Kim et al. (2022) licensed under Creative Commons CC BY 4.0.

^{125}I-seed implantation therapy, improving implantation precision and optimizing dose distribution.

5 Discussion and outlook

In this review, we summarize seven common 3D printing technologies, including the description of the techniques and materials, as well as the common applications. Firstly, using a 3D-printed model, the surgeon can have a full pre-operative conversation with the patient, who can learn about the scope of surgery and the possibility of complications, which often leads to their greater confidence in the operation. Besides, the availability of life-size 3D models has positive implications concerning informed consent and other legal issues. The 3D-printed models are shown to the medical students during the teaching period, which can greatly enhance their understanding of anatomy and physiology as well as facilitate surgical training. The 3D printing technology can be used to create anatomical models for preoperative plans and intraoperative navigation of hepatic tumors, liver transplantation, HC, pancreatic cancer, and so on. Secondly, tumor cell models are printed to evaluate the therapeutic effects of chemotherapy drugs and to screen for better chemotherapy drugs. Finally, 3D printing technology can be utilized to print implants, such as hepatocyte models and bile duct stents. With the further development of research, hepatocyte models have the potential to become one of the sources of human liver donors.

On the other hand, 3D printing technology has some limitations. For example, the pursuit of accuracy in organ modeling tends to make it costly and time-consuming, resulting in models that are not suitable for situations such as emergency surgery or unplanned liver transplants. Furthermore, there is the issue of model accuracy: liver models are less accurate for second-order biliary or portal division, which can lead to serious surgical consequences if the surgeon fails to notice these issues (Jin et al., 2021). There is also a lack of standardization in the manufacturing of 3D-printed models (Goo et al., 2020), which face the same lack of regulation and ethics. The related research is in the early stage on regenerative medicine and tissue engineering. Meanwhile, the results of animal experiments cannot always apply to the human body and be fed back to the treatment of clinical diseases. Therefore, the research on 3D printing technology in regenerative medicine and tissue engineering should be improved, so that 3D printing technology can better serve the diagnosis and treatment of hepatobiliary and pancreatic surgical diseases (Yang et al., 2021).

Nonetheless, our review shows the increasing role of 3D printing technology in hepatopancreatobiliary surgery. It has the potential to become a highly capable tool for surgeons for patient management, surgical planning, and patient and medical education. Further research is needed to build a broader knowledge about the desired functionality and clinical outcomes of 3D-printed products. As 3D printing technology continues to develop its potential in personalized surgery, this will be an exciting time in the coming years for the relevant professionals, from research institutions to hepatopancreatobiliary surgical practices.

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Author contributions

Wujiang SHI and Jiangang WANG compiled the data and wrote the manuscript. Jianjun GAO, Xinlei ZOU, and Qingfu DONG contributed to the data collection. Ziyue HUANG, Jialin SHENG, and Canghai GUAN contributed to the figure and table design. Yi XU, Yunfu CUI, and Xiangyu ZHONG contributed to the manuscript's study design and initial review. All authors have read and approved the final manuscript, and therefore, have full access to all the data in the study and take responsibility for the integrity and security of the data.

Compliance with ethics guidelines

Wujiang SHI, Jiangang WANG, Jianjun GAO, Xinlei ZOU, Qingfu DONG, Ziyue HUANG, Jialin SHENG, Canghai GUAN, Yi XU, Yunfu CUI, and Xiangyu ZHONG declare that they have no conflict of interest.

This review does not contain any studies with human or animal subjects performed by any of the authors.

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