—Review—

# Current Status of Robotic Hepatobiliary and Pancreatic Surgery

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Laparoscopic surgery is performed worldwide and has clear economic and social benefits in terms of patient recovery time. It is used for most gastrointestinal surgical procedures, but laparoscopic surgery for more complex procedures in the esophageal, hepatobiliary, and pancreatic regions remains challenging. Minimally invasive surgery that results in accurate tumor dissection is vital in surgical oncology, and development of surgical systems and instruments plays a key role in assisting surgeons to achieve this. A notable advance in the latter half of the 1990s was the da Vinci Surgical System, which involves master-slave surgical support robots. Featuring high-resolution three-dimensional (3D) imaging with magnification capabilities and forceps with multi-joint function, anti-shake function, and motion scaling, the system compensates for the drawbacks of conventional laparoscopic surgery. It is expected to be particularly useful in the field of hepato-biliary-pancreatic surgery, which requires delicate reconstruction involving complex liver anatomy with diverse vascular and biliary systems and anastomosis of the biliary tract, pancreas, and intestines. The learning curve is said to be short, and it is hoped that robotic surgery will be standardized in the near future. There is also a need for a standardized robotic surgery training system for young surgeons that can later be adapted to a wider range of surgeries. This systematic review describes trends and future prospects for robotic surgery in the hepatobiliary-pancreatic region. (J Nippon Med Sch 2024; 91: 10–19)

**Key words:** robotic surgery, hepato-biliary-pancreatic surgery

## Introduction

Endoscopic images can be transmitted to any location, which allows surgeons to control robotic forceps remotely. Robotic surgery was conceived to allow surgeons to perform surgery in places where they are not physically present (e.g., in remote areas or on battlefields)[1]. It is now more widely recognized for its role in enabling surgery that is less invasive than laparoscopic surgery because it offers three-dimensional (3D) imaging, precise forceps operation, and an anti-tremor function[2]. The advantages of robotic surgery are expected to be apparent in the hepato-biliary-pancreatic region, as the complicated anatomy demands precise dissection, vascular treatment, and reconstruction. In our previous review, we described the status of robotic surgery for the esophagus, stomach, colon, and rectum[3]. In this review, we focus on robotic surgery for the hepato-biliary-pancreatic area.

## Robot-Assisted Hepatectomy

Robot-assisted hepatectomy (RH) has a short history: Giulianotti et al.[4] reported RH for the first time in 2003. It has since become widespread in Europe, the United States, and Asia, and has been applied to lobectomy[5] and donor hepatectomy[6]. In Japan, Uyama et al.[7] first reported it in 2009, but this was performed at their own expense and limited to a few centers.

The advantages of robotic hepatectomy over laparoscopic surgery are the availability of high-definition imagery, the magnified vision effect, multi-articular ability, tremor-filtered articulated function, and motion scaling

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Table 1 Comparative study of laparoscopic and robot-assisted hepatectomy

| Author | Group | Total | Surgical duration (mean±SD, median: range) | Complications (%) | Blood loss (mean±SD, median: range) | Conversion (%) | Duration of hospital stay (mean±SD, median: range) |
|---|---|---|---|---|---|---|---|
| Tsung et al.[14] 2014 | RH | 57 | †253 (180-355) | 11 (19.3) | 200 (50-338) | 4 (7.0) | 4 (3-6) |
| | LH | 114 | †262 (199-333) | 29 (25.4) | 100 (50-350) | 10 (8.8) | 4 (3-5) |
| Croner et al.[15] 2016 | RH | 10 | 321 (138-458) | 1 (10.0) | 306 | NA | 7 (5-13) |
| | LH | 19 | 242 (80-478) | 3 (15.8) | 356 | NA | 8 (4-33) |
| Lai and Tang[20] 2016 | RH | 100 | †207.4±77.1 | 14 (14.0) | 335 | 4 (4) | 7.3 ±5.3 |
| | LH | 35 | †134.2±41.7 | 7 (20.0) | 336 | 2 (6) | 7.1 ±2.6 |
| Berber et al.[21] 2010 | RH | 9 | 258.5 ± 27.9 | 1 (11.1) | 136 ± 61 | 1 (11.1) | NA |
| | LH | 23 | 233.6 ± 16.4 | 4 (17.4) | 155 ± 54 | 0 | NA |

NA: not available, LH: Laparoscopic hepatectomy, RH: Robotic hepatectomy, †: Statistically significant

function, which together allow for more delicate and precise surgical operations[8]. Furthermore, robotic hepatectomy facilitates procedures involving the extrahepatic Glisson capsule, vascular resection, and partial hepatic resection, which uses curvilinear resection planes. These advantages reduce or eliminate the drawbacks of laparoscopic hepatectomy (LH), including restricted movement of forceps during operation, difficulty in spatial recognition, technical difficulty in ligation and suturing, and delay in response to bleeding, thus making the procedure more reliable. In addition to lobectomy and segmental resection, laparoscopic systematic hepatectomy can be performed by subsegmental resection of S2, S3, S4, S5, and S 6; S7 and S8 resection can be performed if they can be approached from the hepatic hilum. Robotic surgery may enable surgery for tumors that occupy the S1, S4b, S7, and S8 areas, which is difficult in LH[9].

RH is used worldwide for liver transplant donor surgery[10], and indications are being evaluated at each center. In Japan, RH is indicated for tumors with a diameter of ≤10 cm and liver tumors without invasion into major vessels. These are considered tumors, and there are no restrictions on the area occupied by the tumor. RH is often indicated for liver tumors in S1, S7, and S8, which are difficult to treat laparoscopically[11].

Device issues—a drawback of the da Vinci system—were addressed by commercializing ultrasonic coagulation incision devices, vessel sealers, and staplers. However, as there is no Cavitron Ultrasonic Surgical Aspirator, it is necessary to use the clamp-crush method for liver transection[12]. Recent upgrades have enabled the use of firefly mode using indocyanine green (ICG), facilitating tumor identification and systematic hepatectomy[13]. Thus, da Vinci devices have been gradually expanded to close the gap between LH and RH.

Several studies have compared the short-term results of RH and LH. Tsung et al.[14] reported that although the operation time for the RH group was longer, there were no differences in other surgical results. Croner et al.[15] reported that RH yielded almost the same postoperative results as LH. A systematic review by Montalti et al.[16] reported that an RH group had more bleeding and a longer operation time, but the laparotomy conversion rate, R1 rate, postoperative complications, and length of hospital stay were similar. Thus, although the safety of RH is comparable to that of open hepatectomy (OH) and LH, many reports indicate that the operation time was longer than for LH[14,17]. Unless prolonged operation time affects safety and oncological results, RH is useful and can be applied for difficult anatomical hepatectomy and hepatectomy with vascular reconstruction, which are difficult with LH[18].

Regarding the long-term results of RH, Chen et al.[19] reported that the relapse-free survival rate for hepatocellular carcinoma (HCC) cases (91.5% in 1 year and 72.2% in 3 years) was not different from that of OH at the same center. Moreover, the 1- and 3-year survival rates were 100% and 92.6%, respectively, which were not significantly different from the rates for OH. Lai and Tang[20] reported no significant difference between LH and RH for HCC. Berber et al.[21] compared LH with RH for liver tumors, including metastases, and observed no significant difference (**Table 1**).

Use of minimally invasive hepatectomy utilizing robots is increasing worldwide and is expected to spread in Japan, as the procedure was approved for insurance coverage in 2022. Compared to OH, LH results in significantly fewer complications, shorter hospital stays, and less blood loss when performed by experienced physicians. However, long-term outcomes were similar for LH and

OH[22].

The surgical cost is greater for robotic surgery than for laparoscopic surgery, and future prospective studies will therefore need to demonstrate advantages over laparoscopic surgery, if possible. Moreover, as LH progresses, its limitations will likely become clearer, as will the ways that robots can be effectively used and the target diseases for which it is indicated.

## Robot-Assisted Pancreatectomy

Robot-assisted pancreatoduodenectomy (RPD) and robot-assisted distal pancreatectomy (RDP) were performed for the first time in 2003 by Giulianotti et al.[4]. Melvin[23] reported RDP later that year, and reports of robot-assisted pancreatectomy (RP) have been increasing in Europe, the United States, and China. In Japan, the first RPD report was performed in 2011 by Horiguchi et al.[24]

Laparoscopic pancreatectomy is indicated for pancreaticoduodenectomy, distal pancreatectomy, central pancreatectomy, and enucleation, as is RP. RP for pancreatic cancer is considered technically equivalent to laparotomy, including dissection of lymph nodes; therefore, the indication for RP is thought to be for cases without hepatic artery infiltration, portal vein infiltration, and superior mesenteric vein infiltration that can be operated on for an R0 resection.

In the multicenter LEOPARD study[25], minimally invasive distal pancreatectomy, including laparoscopic-assisted distal pancreatectomy (LDP) and RDP, was associated with significantly longer operation times than open distal pancreatectomy (ODP); however, intraoperative bleeding was limited, and the length of hospital stay after surgery was significantly shorter. Furthermore, the incidence of complications of CD (Clavien-Dindo) classification Grade IIIa or higher, pancreatic fistula, and readmission rate did not significantly differ from the values for ODP. Consequently, LDP is currently the standard procedure for benign disease and benign-malignant borderline lesions such as pancreatic cystic tumors. However, technical and oncological issues make LDP for malignant tumors difficult. Ohtsuka et al.[26] devised a scoring system for the technical difficulty of LDP with advanced procedures such as radical antegrade modular pancreatosplenectomy, pancreatic body lesions, adjacency to major vessels, peripancreatic extension, and left portal hypertension. These variables significantly affected the difficulty score and are good indicators of difficulty. The technical features that make RDP superior to LDP are improvements in anatomical recognition ability with extremely high-quality 3D images and of operability by forceps, which enables articulated movement. It is clearly useful for exfoliation around major arteries and for dorsal pancreatic exfoliation, as in radical antegrade modular pancreatosplenectomy. These technological innovations will likely overcome the challenges of LDP.

In a meta-analysis by Zhang et al.[27] in 2013, which compared 137 RDP and 203 ODP cases, overall complications, reoperation rates, and positive margin rates were significantly lower for RDP than for ODP. However, there was no difference in postoperative pancreatic fistula and mortality, and RDP was as safe as ODP. Zureikat et al.[28] reported that the rate of conversion to laparotomy from RDP was 2% in 250 RDP cases, which was significantly lower than that of LDP and is thus an advantage of RDP. The reason for the low conversion rate is that manipulation around the larger blood vessel is straightforward, avoiding bleeding due to vessel injury; when unexpected bleeding does occur, the suturing is easier in robot-assisted surgery than in laparoscopic surgery. Daouadi et al.[29] reported that RDP and LDP had similar short-term postoperative outcomes and that RDP for malignant tumors was more useful than LDP for lymph node dissection and R0 resection because of its high operability and good visibility. Liu et al.[30] used propensity score matching (PSM) to compare RDP and LDP in 102 cases and observed that RDP significantly reduced the conversion rate and yielded better spleen-preserving and splenic vein-preserving rates than LDP. Moreover, RDP significantly shortened the length of hospital stay after surgery. Thus, RDP appears to sufficiently compensate for the technical disadvantages of LDP (**Table 2**).

Although RDP for pancreatic cancer is expected to be superior to LDP, no large-scale RCT has compared RDP and LDP; most studies were retrospective observational studies. Future high-quality, large-scale studies should carefully evaluate postoperative complications and long-term outcomes in pancreatic cancer as the primary endpoints.

Conversely, reports of RPD are similar to those of RDP. A multicenter study in the United States in 2016 compared 211 RPD and 817 OPD cases: RPD significantly extended surgery time while significantly reducing bleeding and severe complications. No significant differences existed between the 90-day mortality rate, pancreatic juice leakage rate, length of hospital stay, and 90-day readmission rate[31]. In a study by McMillan et al.[32] and Wang et al.[33] that used PSM to compare RPD with OPD, operation time was longer with RPD; however, less

Table 2 Comparative study of robot-assisted pancreatectomy

| Author | Group | total | Surgical duration (mean±SD, median: range) | Complications (%) CD III≥ | Pancreatic fistula (%) | Blood loss (mean, median: range) | R1 rate (%) | Conversion (%) | length of hospital (mean±SD, median: range) |
|---|---|---|---|---|---|---|---|---|---|
| De Rooij et al.[25] 2019 | RDP+LDP | 51 | †217 (135-277) | 13 (25) | 20 (39) | †150 (50-350) | NA | 8 | †6 (4-13) |
| | ODP | 57 | †179 (129-231) | 21 (38) | 13 (23) | †400 (200-775) | NA | - | †8 (6-12) |
| Daouadi et al.[29] 2013 | RDP | 30 | †293 ± 93 | 6 (20) | 14 (46) | 150 (100-300) | †0 | †0 | 6.1 ± 1.7 |
| | LDP | 94 | †372± 141 | 13 (14) | 39 (41) | 150 (100-300) | †36 | †15 (16) | 7.1 ± 4.0 |
| Liu et al.[30] 2017 | RDP | 102 | 207.1 ± 65.5 | 5 (4.9) | 31 (30.4) | 100 (50-200) | NA | †3 (2.9) | †7.7 ± 2.2 |
| | LDP | 102 | 199.6 ± 66.8 | 6 (5.9) | 36 (35.3) | 100 (50-100) | NA | †10 (9.8) | †8.6 ± 3.6 |
| Zureikat et al.[31] 2016 | RPD | 211 | †402 (257-685) | 50 (23.7) | †29 (13.74) | †200 (30-4,500) | †50 | 10 (4.7) | 8 (4-58) |
| | OPD | 817 | †300 (107-840) | 195 (23.9) | †74 (9.08) | †300 (20-7,350) | †31 | - | 8 (4-148) |
| Wang et al.[33] 2018 | RPD | 87 | †455± 139 | 8 (9.1) | 7 (8.0) | †120 (1-1,000) | 3.4 | 10 | 26± 16 |
| | OPD | 87 | †375± 78 | 5 (8.0) | 11 (12.6) | †250 (30-1,000) | 5.7 | - | 27± 18 |
| Nassour et al.[34] 2017 | RPD | 193 | 422 | 81 (42.0) | 20.8 | NA | NA | †22 (11.4) | 10.7 |
| | LPD | 235 | 429 | 96 (40.9) | 19.9 | NA | NA | †61 (26.0) | 10.6 |

LDP: Laparoscopic distal pancreatectomy , ODP: Open distal pancreatectomy , RDP: Robotic distal pancreatectomy
†: Statistically significant, NA: not available

bleeding occurred, and more lymph nodes were dissected with RPD. Furthermore, delay in gastric emptying was less severe in robot-assisted surgery, and there was no significant difference in postoperative complications. The rate of postoperative pancreatic juice leakage was 8.0% in RPD and 12.6% in OPD. Survival rates at 1, 2, and 3 years after RPD surgery were not inferior to those after OPD. RPD was not inferior to OPD in postoperative pancreatic juice leakage, surgical risk, or short-term outcomes.

There are few reports comparing RPD and LPD (laparoscopic pancreatoduodenectomy). Using a database of ACS-NSQIP, Nassour et al.[34] compared 193 RPD and 235 LPD cases and investigated factors associated with total complications within 30 days after pancreatoduodenectomy (PD) by minimally invasive surgery. High body mass index, combined resection of blood vessels, and long surgical time were associated with development of complications. Although the difference in surgical procedure between RPD and LPD did not affect the incidence of complications within 30 days, it had a significant role when laparotomy conversion was concerned. They argued that the operability and anatomical recognition of robotic surgery are useful for complex gastrointestinal reconstruction and control of bleeding, thus leading to a lower conversion rate (**Table 2**).

A technical document[24,34] highlights the superiority of RPD over LPD in the reconstruction of PD. The advantages include the magnifying effect of the 3D camera, with improved freedom of movement in the abdominal cavity, better stability during the procedure, and the use of forceps with higher degrees of freedom. For pancreatic cancers, R0 resection is an important factor that prolongs survival, especially in pancreatic head cancer[35]. The sites where the tumor may be exposed in the surgical procedure include the posterior exfoliated surface of the pancreas, the incisal stump of the pancreas, the portal vein running part, and the second part of the pancreatic head plexus. To perform reliable R0 excision, these sites must be considered and sophisticated technique is required. The proven superiority of the R0 resection rate for RPD[36] and similar results regarding the number of lymph node dissections[37] indicate that RPD is a valid surgical procedure for pancreatic head cancer. However, the reports cited were mostly nonrandomized observational studies, and further evidence-based analysis is required to confirm the oncological benefits of RPD.

In Japan, with the revision of medical fees in April 2020, RDP and RPD for pancreatic tumors, including pancreatic cancer, will be covered by insurance, and it is expected that uptake of RDP and RPD will be rapid[38]. Conversely, in the United States, the 30-day postoperative mortality rate of minimally invasive pancreatoduodenectomy (MIPD; LPD and RPD) for malignant tumors has an inverse correlation that increases in centers where fewer surgeries are performed. In fact, the mortality rate was about twice that of open surgery in centers with fewer than 10 cases in 2 years[39].

In Japan, the surgery-related mortality rates for LDP and LPD are 0.3% and 0.4%, respectively, because of the safety management system established by academic societies, including prospective registration, which makes surgery safer than in other countries[40]. Facility standards for LPD and RPD are also stricter, and it is stated that "surgery related to the pancreas is performed in 50 or more cases per year (of which 20 or more are PD per year)"[41]. However, extreme concentration of centers may lead to technical disparities between facilities in and outside Japan, and determining safe dissemination of endoscopic pancreatic surgery is important.

## Robotic Surgery for Biliary Tract Cancer

As previously described, the first trans-Atlantic human robotic telesurgery was performed for a cholecystectomy[1]. Cholecystectomy for cholelithiasis is a simple procedure and is selected as a basic training model for the most common hepatobiliary surgery in the early stages of robotic surgery. After 20 robotic cholecystectomies, even including acute cholecystitis, the operative time, morbidities, and length of hospital stay were similar to those of conventional laparoscopic cholecystectomy, and the conversion rate to open laparotomy was low[4]. The most compelling indications for robotic surgery are procedures that involve a narrow and deeply fixed surgical field; minimally invasive surgery requires extreme accuracy and fine dissection and suturing. Surgery for biliary malignant tumors falls under this category. Surgical procedures for biliary tract cancer vary depending on the site and extent of the lesion. However, PD is the standard surgery for distal bile duct cancer and carcinoma of the papilla of Vater.

In Japan, LPD and RPD have been covered by insurance since April 2020[38]. It has thus become possible to perform laparoscopic surgery for distal bile duct cancer and carcinoma of the papilla of Vater. In addition, from April 2022 insurance coverage for laparoscopic surgery accompanied by gallbladder bed resection was approved for gallbladder cancer[42]. However, insurance does not cover laparoscopic surgery for hilar cholangiocarcinoma and gallbladder cancer with biliary reconstruction.

In the hepatoduodenal ligament, the intersection of the bile duct, portal vein, and artery is complicated[43]. The artery divides into many branches and burrows into the dorsal side of the lumen to be preserved. The prognosis for biliary tract cancer with lymph node metastasis is poor, regardless of site, and innovation in surgical resection alone does not improve outcomes in these cases[44]. Nevertheless, thorough vascular and lymph node dissections are essential for local tumor growth control. To be accepted as the standard, laparoscopic and robot-assisted surgeries must achieve a similar dissection area and postoperative results as open surgery. In malignant biliary disease, both laparoscopic and robot-assisted surgeries are in the exploratory stage; currently, short-term results evaluating safety (based on case reports and prospective case accumulation) and long-term results centered on curability are being verified.

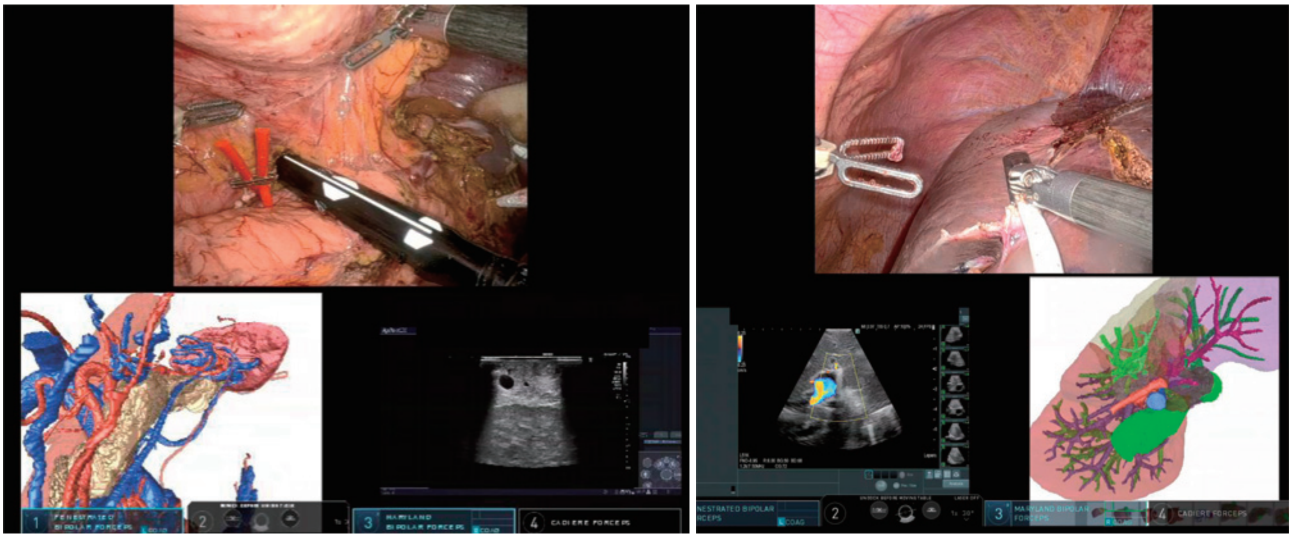
Since malignant biliary disease is associated with high rates of recurrence and poor prognosis, and the benefits of adjuvant therapy remain unclear at present, for treatment, sufficient caution should be exercised in radical surgery, safety, and indications. In both PD and hepatectomy, the manipulation of stripping around the hepatic artery, including lymph node dissection, is considered a focal point for generalization. Information on long-term outcomes of LPD and RPD cases for distal bile duct cancer and carcinoma of the papilla of Vater need to be collected and analyzed. However, it has been reported that the number of lymph node dissections and the R0 resection rate are not different from those of open surgery[45,46].

There are many surgical procedures for gallbladder cancer, such as gallbladder bed resection, S4a + 5 resection, (extended) right hepatic lobectomy, and hepatopancreatoduodenectomy, which vary in relation to the degree of progression and lesion extent. In clinical practice, it may be difficult to distinguish it from cholecystitis, and some laparoscopic surgeries are performed for patients with suspected gallbladder cancer of T1 and T2. The frequency of incidental gallbladder cancer after gallbladder resection performed with a diagnosis of cholecystitis is 0.2 to 1.0%[47], and for gallbladder cancer with a final diagnosis of T2 or higher, additional liver resection with lymph node dissection is recommended[48].

Multiple clinical studies of laparoscopic surgery have been reported for gallbladder cancer[49,50], and long-term outcomes were equivalent to those for open surgery for gallbladder cancer up to T2. A study[51] that used PSM to compare the short-term results of robot-assisted surgery and open surgery for gallbladder cancer deeper than T2 found no significant differences in surgery time, bleeding volume, postoperative complication rate, or number of lymph node dissections. Moreover, the length of hospital stay after surgery was significantly shorter after robot-assisted surgery.

In contrast, the Japanese biliary tract cancer clinical practice guidelines (revised 3rd edition)[48] do not recommend laparoscopic surgery for patients with suspected gallbladder cancer, because of concerns such as incomplete cancer resection, intraperitoneal bile spillage due to gallbladder injury, and recurrence at port sites.

Outside of Japan, extended right lobectomy and right hepatic trisegmentectomy for hilar cholangiocarcinoma



a b

Fig. 1 Robotic "split-view".
Using a dedicated probe and specific software, the surgeon can change from an endoscopic to an ultrasound view or create a split-view with both the images. In this figure, a 3D model is concurrently added intraoperatively to monitor the tumoral vascular relationship studied preoperatively.
(a) The relationship between tumor localization and blood vessels during RDP.
(b) The distance to major blood vessels and portal vein blood flow during RH.

have already been performed by robot-assisted surgery[52]. However, in Japan, hepatectomy requiring biliary reconstruction for hilar cholangiocarcinoma has a higher mortality rate than other surgical procedures, even with open surgery[53], and laparoscopic surgery is not recommended. Hepatectomy for biliary malignancies is difficult because a different hepatectomy line is needed to remove the caudate lobe, the arteries and portal veins need to be dissected near the dissection limit, and biliary reconstruction is required.

Wang et al.[54] reported a systematic review of 23 studies including 205 cases of laparoscopic surgery (LS) and robot-assisted surgery (RS) for hilar cholangiocarcinoma. The R0 excision rate, operation time, and bleeding volume were 80.1% (LS 85.9%, RS 71.0%), 458.4 minutes (LS 423.3 minutes, RS 660.8 minutes), and 615.3 mL (LS 52 mL, RS 1,188.5 mL), respectively. The conversion rate, postoperative complication rate, and perioperative mortality rate were 9.1% (LS 12.2%, RS 3.8%), 47.2% (LS 38.4%, RS 61.0%), and 3.0% (LS 4.0%, RS 2.0%), respectively, and there was room for improvement in results and outcome.

In the future, it may be possible to overcome the difficulties of hilar cholangiocarcinoma surgery by improving surgical skill in LS and by advancing robot-assisted surgical instruments. Bile duct resection generally requires anastomosis between the pancreas, the extrahepatic and intrahepatic bile ducts, and gastrointestinal tract. Anastomosis, including pancreaticojejunostomy, is difficult even in open surgery and sometimes causes life-threatening complications. In this regard, robotic surgery has advantages such as the magnified vision effect of the 3D camera with an improved degree of freedom in the abdominal cavity, stability during the operation, degree of freedom of forceps, and expected improvement of results.

## New Technology

Although minimally invasive hepatobiliary pancreatic resection has better short-term outcomes than open surgery, it is technically more challenging. However, image-guided surgical navigation systems have been developed to overcome the challenges[55], and computed tomography (CT) images that had previously been used for diagnostic purposes can now be used to facilitate treatment. Before the development of volume rendering, traditional surgery relied on direct visual observation and preoperative image evaluation, where clinicians had to transform diagnostic reconstructions into 3D images in their minds[56]. However, image-guided surgical navigation systems have made it possible to display 3D images on monitors[57]. The da Vinci system TilePro feature provides safe and reliable navigation by displaying 3D images in the surgical field (**Fig. 1a, 1b**), making it possible to accurately grasp the complex course of blood vessels during surgery and the

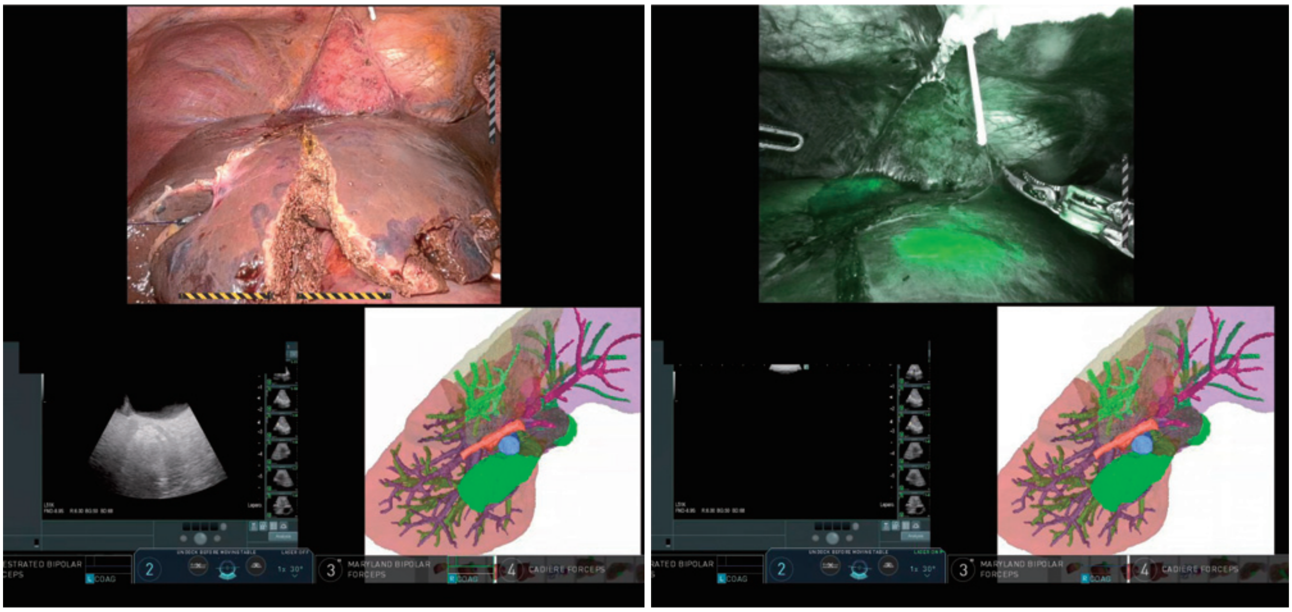


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Fig. 2 Fluorescence imaging of a hepatic tumor.

(a) White-light color image.

(b) Fluorescence imaging after preoperative intravenous injection of ICG clearly showing an HCC in hepatic segment II as a rim-fluorescing lesion during robotic hepatectomy.

relationship between the anterior and posterior organs[58]. Surgery in the hepatobiliary system relies on precise localization of lesions and detailed knowledge of patient-specific vascular and biliary anatomy, so detailed 3D anatomical information facilitates complete tumor removal and preservation of sufficient functional liver tissue. In addition, the firefly feature (real-time intraoperative fluorescence guidance using near-infrared imaging after ICG injection) can be used in various surgical disciplines to visualize anatomy, assess tissue perfusion, and identify and locate tumors[59]. In liver surgery, it helps identify subcapsular liver tumors. Primary and secondary hepatic malignancies can be identified via impaired bile excretion in cancerous tissue of HCC and in noncancerous liver parenchyma surrounding adenocarcinoma foci (**Fig. 2a, 2b**). The firefly feature can also be used to identify liver segments: hepatic segment borders can be visualized by injecting 0.25-2.5 mg/mL ICG into the portal vein or by intravenously injecting 2.5 mg ICG after clamping the proximal portal branch toward the liver region to be removed. These techniques allow identification of liver segments before hepatectomy and during parenchymal section for anatomical resection[60].

Augmented reality technology, in which artificial intelligence is used to process preoperative CT images, enables visualization of invisible anatomical structures via a 3D virtual model overlaid on the operative field. The surgical resection plane can also be delineated and vessels selectively ligated, allowing safe and accurate intraoperative recognition of all major vascular structures, and in turn enabling liver resection without vascular clamping and with negative resection margins[61,62]. Augmented reality technology thus transforms surgical interventions, making them safer, easier, and faster. These new techniques will also revolutionize surgical education by facilitating the transfer of knowledge and skills to young surgeons[63].

## Learning Curve

The learning curve to achieve competence in robotic surgery involving the esophagus, stomach, and colon is shorter than that to achieve competence in LS[64–66]. For hepatectomy, the median learning curve for LH and RH was reported to be 50 cases and 25 cases, respectively[67]. As for PD, the learning curve is considered to be 40 cases, with significant differences reported in the amount of bleeding, hospitalization period, and operation time between the first 40 cases and remaining 60 cases[68]. Zureikat et al.[69] stated that performing robotic pancreatectomy 100 times or more halved the number of complications. It is also noteworthy that in the ROLLAR trial the rate of conversion to open surgery in the RS group was correlated only with the surgeons' experience of robotic surgery, not the number of laparoscopic surgeries they had performed[66]. In other words, experience of LS is not necessarily required to carry out robotic surgery. Such findings will guide discussions of operator regulation, along with the future introduction and popularization of RS.

## Conclusion

Although robotic surgery is expensive and involves long operation times, it will continue to spread and develop. Surgery in the hepato-biliary-pancreatic region is complicated, so although robotic surgery can be used safely, it is recommended that it be performed at specialized centers. The short-term and long-term results are expected to be similar to those obtained with open surgery, but solid evidence from RCTs and other high-quality studies needs to be compiled. In the future, further development of robotic equipment can be expected to make robotic surgery equal to or better than open surgery in terms of precise excision, dissection, and reconstruction. The learning curve is also short, and new technology makes the transfer of knowledge and skills to young surgeons easier, signaling a revolution in surgical education methods. In the future, it is likely that factors such as the inclusion of robotic surgical procedures in insurance coverage, the relaxation of facility standards, and greater subsidization of medical fees will lead to uptake of the technology in general medical practice.

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