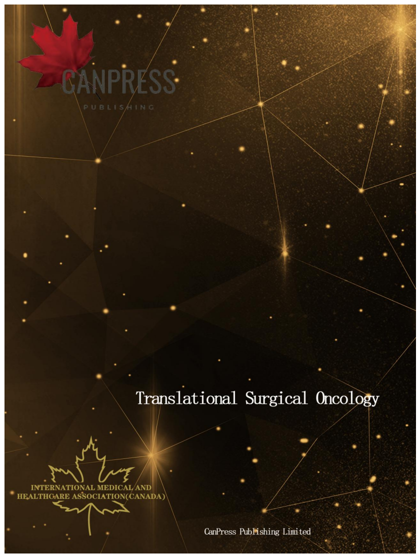
Current Status and Prospects of Robotic Hepatobiliary Surgery



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Abstract

In recent years, the application of robotic surgery (RS) in hepatobiliary surgery has increased. The benefits of RS in certain hepatobiliary diseases have been demonstrated. However, the safety, efficacy, and learning curve of robotic hepatobiliary surgery are still controversial. Therefore, in this review we aim to summarize recent research progress and current applications of robotic hepatobiliary surgery. In addition, we highlight the prospects of robotic hepatobiliary surgery in coming years.

Keywords: hepatobiliary disease; robotic hepatobiliary surgery; laparoscopic surgery

Introduction

To date, nearly all types of hepatobiliary procedures can be performed through minimally invasive surgery, represented by laparoscopic surgery[1]. Compared with open surgery, laparoscopic surgery offers the advantages of less blood loss, less postoperative pain, faster functional recovery, and shorter hospital stays, leading to its widespread adoption[2, 3]. As an evolution of laparoscopic surgery, robotic surgery (RS) was first proposed as a remote operation system in the late 1990s[4]. RS provides 3-dimensional (3D) views, better flexibility, and minimizes the impact of surgeon hand tremors[5]. The robotic system also offers ergonomic advantages, reducing surgeon fatigue (Figure 1)[5]. RS has been practiced in various simple and complex hepatobiliary surgeries, demonstrating preliminary feasibility and safety[6-8]. However, the robotic system has limitations, such as the lack of tactile feedback and high equipment costs[9, 10]. The safety, efficacy, and learning curve of robotic hepatobiliary surgery still lack consensus[11-15]。
Therefore, in this review we aim to summarize recent research progress and current applications of robotic hepatobiliary surgery. In addition, we highlight the prospects of robotic hepatobiliary surgery in coming years.

Robotic Liver Surgery

Feasibility and Safety

The 2008 Louisville Statement stated that the best indication for laparoscopic liver resection is solitary lesions, 5 cm or less, located in liver segments 2 to 6[16]. The application of robotic liver surgery (RLS) is more cautious (Figure 2). In 2003, Giulianotti et al.[17] first reported the technical experience of robotic liver wedge resection and segmentectomy. With accumulated expertise in robotic surgery and technological innovation, surgeons have successfully performed robotic wedge resection, segmentectomy (including lesions in the posterosuperior segments), central hepatectomy, and hemihepatectomy[18-22]. Additional studies reported the successful performance of complex RLS procedures. Broering et al.[23] reported three cases of fully robotic donor hepatectomy and recipient liver graft implantation, successfully performing anastomoses of the portal vein, hepatic artery, and bile duct. Robotic associating liver partition and portal vein ligation for staged hepatectomy (ALPPS) [24-26], as well as the removal of inferior vena cava tumor thrombus[27], have also been demonstrated to be feasible and safe.
RLS shows comparable safety to open and laparoscopic liver surgery. A retrospective multicenter study compared the

outcomes of robotic liver resection (RLR) and open liver resection (OLR) in patients with hepatocellular carcinoma (HCC) of diameter ≥5 cm[28]. After propensity score matching (PSM), the robotic group demonstrated shorter operative times, lower estimated blood loss (EBL), and shorter length of stay (LOS)[28]. There were no significant differences between the two groups in recurrence-free survival (RFS) or overall survival (OS)[28]. Long et al.[29] compared the effects of RLR and laparoscopic liver resection(LLR) in patients with liver malignancies. The two methods had similar surgical results regarding operation time, conversion to open surgery rate, and overall complication rate. In terms of oncology, the 5-year OS and disease-free survival (DFS) of the two groups were also comparable[29]. A history of abdominal surgery is generally considered a disadvantage for minimally invasive liver surgery due to the risk of abdominal adhesions[30]. In patients who had undergone open liver hepatectomy, Birgin et al.[31] found no significant difference in postoperative complication rates between robotic or laparoscopic (= minimally invasive) repeat liver resection and open repeat liver resection. In addition, robotic segmentectomy and wedge resection have also demonstrated favorable outcomes in patients with liver cirrhosis[32]. These researches indicate that RLS is safe and feasible. Based on its safety and feasibility, RLS has been adopted for primary HCC, liver metastasis, hepatic hemangioma, liver cyst, and hepatic cystic echinococcosis[28, 33-36].

Short-term Outcomes

Short-term results include intraoperative results (such as operation time, blood loss, open conversion), LOS, complications, readmission, and mortality[37]. Compared to open liver surgery, RLS offers the typical advantages of minimally invasive surgery. RLS is associated with a lower EBL, shorter LOS, and quicker recovery (Table 1)[38]. However, RLS often involves longer operative times[39], and the docking of the robotic system and instrument changes potentially prolong the procedure[40]. Troisi et al.[41] conducted a retrospective, multi-center, propensity score-matched analysis on right lobe donor hepatectomies. Compared with open procedures, robotic procedures had a longer operative time (493±96 minutes vs 358±95 minutes, $p<0.001$) but less blood loss and pain[41]. There was no significant difference in overall and major complications (≥ IIIa)[41]. Di Benedetto et al.[39] also reported that RLR had a significantly longer operative time than OLR (median [interquartile range (IQR)], 295 [190-370] minutes vs. 200 [165-255] minutes, $P<0.001$), but a shorter hospital stay, fewer admissions to the intensive care unit (ICU) after surgery, and a lower incidence of severe postoperative complications[39]. Operative time was identified as a risk factor for postoperative complications after LLR[42]. Although RLS is associated with longer operative time, it maintains favorable short-term effects.

Early studies reported that compared with LLR, RLR did not show advantages in short-term outcomes but required longer operation time[37, 40]. However, a recent meta-analysis of 22 PSM studies demonstrated that RLR had less blood loss and a lower open conversion rate, although the study heterogeneity was high (I2=84% and I2=45%)[43]. Additionally, RLR was superior regarding severe complications, with minimal heterogeneity ($I^2 = 0\%$)[43].

Cipriani et al.[44] compared LLR and RLR according to different levels of difficulty. RLR achieved better intraoperative outcomes in high-difficulty resections, while no differences were observed for intermediate and low-difficulty resections[44]. Chong et al.[45] reported that the robotic method was more commonly adopted in cases with high difficulty levels than the laparoscopic method. Among several hepatectomy difficulty scoring systems, lesion location and resection extent are common variables, with lesions in the posterosuperior segments and major hepatectomy associated with higher difficulty[46]. RLR had a higher proportion of major hepatectomies (27% vs. 2.9%) and tumors located in posterosuperior segments (29% vs. 0%) than LLR[47]. Major hepatectomy is defined as the resection of ≥3 contiguous Couinaud liver segments, including left hepatectomy (LH) /extended left hepatectomy (ELH) and right hepatectomy (RH) /extended right hepatectomy (ERH)[48]. In elderly patients undergoing major hepatectomy, RLR demonstrated shorter LOS, cumulative LOS, and lower rates of ICU admission than LLR[49]. Robotic surgery was also associated with lower open conversion rates in LH/ELH and RH/ELH[50-52]. An international multicenter study of 4822 patients performed PSM and coarsened exact matching (CEM) analyses comparing robotic and laparoscopic major hepatectomies[48]. The robotic group was superior in terms of blood loss, rates of Pringle maneuver (portal triad clamping), and conversion to open surgery[48]. However, after the learning curve of minimally invasive liver resection, the difference in open conversion rates was no longer significant[51]. Furthermore, converted robotic procedures showed inferior outcomes compared with converted laparoscopic procedures, including increased blood loss, blood transfusion rate, postoperative major morbidity, and 30/90-day mortality[53].

Liver resections of the posterosuperior segments (1, 4a, 7, 8) are technically demanding procedures due to the relative inaccessibility and proximity to major vascular structures[54]. These procedures are identified as predictive factors for conversion in LLR[55]. Traditional rigid laparoscopic instruments are challenging to maneuver in the sub-diaphragmatic space[56]. In contrast, the robotic system's seven degrees of freedom theoretically offer technical advantages in precise dissection and hemorrhage control, potentially making it particularly beneficial for posterosuperior segmentectomy[56]. D'Silva et al.[57] conducted PSM and CME analyses on patients from 24 centers who underwent either robotic or laparoscopic posterosuperior segmentectomy. In both analyses, the robotic group had significantly shorter median operative times, lower median blood loss, and fewer cases with blood loss ≥ 500 mL than the laparoscopic group[57]. Another international multicenter study reached similar conclusions and further observed these advantages in the subgroup of patients with liver cirrhosis[54].

Left lateral sectionectomy (LLS), defined as the resection of segments 2 and 3, is considered the simplest anatomic liver resection[58]. Laparoscopic LLS has been shown to have superior outcomes to open surgery[58]. However, compared with laparoscopic surgery, robotic LLS has not demonstrated advantages in perioperative outcomes but is instead associated with increased operative time and costs[58, 59]. Salloum et al.[58] reported that robotic LLS had longer operative time than laparoscopic LLS (203±87 minutes vs 140±33 minutes, p=0.02), with a trend toward an increased blood loss (265±253 ml vs 121±99 ml, p=0.06). In complex cases, robotic LLS was associated with less EBL (131.9 ml vs 320.8 ml, p=0.003)[59].

Long-term and Oncological Outcomes

Radical resection of malignant tumors is essential. Several studies have shown that RLR achieves comparable R0 resection rates to OLR[34, 38, 39, 60] and RLR[37, 43, 61-63]. A study conducted in patients with HCC showed the R0 resection rate was comparable between the OLR and RLR groups (100% vs 99.1%), as was the resection margin distances (median [IQR], 9 [5-10] vs 8 [3-10] mm, p = 0.56[39]). Chang et al.[34] found no significant difference in the R0 resection rate of liver lesions between robotic and open methods for simultaneous resection of rectal cancer and liver metastases. In an international multicenter PSM study involving 10,075 patients, RLS had better R0 resection margins than laparoscopic surgery (89.8% vs 86%, p = 0.015)[52]. In subgroup analyses based on resection extent, no significant difference in the R0 resection rate was found[52]. Some studies have reported that RLS was associated with a higher percentage of lymph nodes examined[64] and a wider margin length [65], but no clear prognostic benefit was demonstrated.

RLR, LLR, and OLR achieved comparable outcomes in terms of long-term survival analysis (Table 2). A recent prospective cohort study evaluated the long-term results of RLR, LLR, and OLR in the treatment of Barcelona Clinic Liver Cancer stage 0-A HCC[60]. There were no significant differences in the 5-year DFS (LLR: 54.4%, RLR: 50.6%, and OLR: 63.8%) or OS rates (LLR: 78.6%, RLR: 75.7%, and OLR: 80.8%) among the three groups, nor in the rates and location of recurrence[60]. However, several studies have reported better prognoses with robotic surgery in HCC patients. Sucandy et al.[38] prospectively followed 183 consecutive patients who underwent robotic or open major hepatectomy for malignant liver tumors. The robotic cohort had a statistically significantly superior estimated median OS over the open cohort (38 months vs. 26 months, p<0.05), and this advantage was mainly observed in the HCC subgroup[38]. Another research found that the RLR group exhibited improved recurrence-free survival (RFS) (median of 65 months vs. 56 months, p = 0.006)[37]. Multivariate Cox regression analysis demonstrated RLR (HR: 0.586, 95% CI (0.393-0.874), p = 0.008) as an independent predictor of reducing recurrence rates and enhanced RFS[37]. In elderly HCC patients, RLR resulted in similar OS and RFS as OLR[66].

In patients with intrahepatic cholangiocarcinoma (iCC) and colorectal liver metastases (CRLM), robotic surgery does not appear to offer significant oncological or survival advantages[38]. A single-center randomized controlled trial (RCT) reported that in patients with simultaneous resection of rectal cancer and CRLM, the 3-year DFS rate (39.5% vs. 35.3%, p=0.739) and 3-year OS rate (76.7% vs. 72.9%, p=0.712) were not statistically significant between RLR and OLR[34]. The long-term survival outcomes of RLR for CRLM have still not been thoroughly studied[67]. In patients with iCC, multivariate Cox analysis showed that the OS was regardless of RLR or OLR (HR 0.71, 95%CI 0.40-1.27; P=0.249) [68].

Robotic Biliary Surgery

Robotic Cholecystectomy

Cholecystectomy is one of the most common procedures in hepatobiliary surgery. Since its introduction, laparoscopic cholecystectomy (LC) has soon become the standard surgical approach for most gallbladder diseases[69].

In recent years, the use of robotic cholecystectomy (RC) has increased yearly, with its adoption in the United States rising from 0.1% in 2010 to 5.25% in 2019[12]. Although RC and LC demonstrate superior outcomes compared to open cholecystectomy[70], RC has not shown a clear advantage over LC.

Kalata et al.[12] retrospectively analyzed 1,026,088 patients who underwent RC or LC based on a database. RC was associated with a higher incidence of bile duct injury necessitating a definitive operative repair within one year compared to LC (0.7% vs 0.2%; relative risk, 3.16 [95% CI, 2.57-3.75])[12]. Another database-based analysis also showed that RC was more likely to have open conversions, bile duct injuries, and major reconstructive interventions[69]. The complication rate of RC was also greater than that of LC[71]. Although the rate of bile duct injury after RC has decreased with increasing experience, most surgeons do not yet perform enough to reach equivalence with LC[72]. Additionally, RC is associated with longer operative time[73, 74], higher conversion rates, longer median LOS, increased readmissions, and higher hospitalization costs[69].

In recent years, some centers have adopted single-site robotic systems for cholecystectomy. Single-site robotic system was reported to reduce incisional morbidity and improve cosmetic outcomes, while retaining the flexible wristed instruments and 3D visualization[75]. Compared with single-incision laparoscopic cholecystectomy(SILC), single-site robotic cholecystectomy (SSRC) had a lower incidence of bile leakage due to perforation of the gallbladder (6.7% vs 17.3%, p=0.019)[76] and lower pain scale scores[77]. However, the cost of SSRC was also significantly higher than SILC[76], and the limited clinical benefits of SSRC do not yet seem sufficient to offset the additional costs.

Robotic Surgery for Cholelithiasis

Cholecystectomy is the standard procedure for gallbladder stones [71], with the current status of RC having been detailed previously. Endoscopic retrieval of common bile duct stones with retrograde cholangiopancreatography (ERCP) has been adopted as the primary treatment modality for extrahepatic biliary stones[78]. Laparoscopic common bile duct exploration (LCBDE) is also an effective treatment, especially after the failure of ERCP or stones refractory to extraction[78]. In recent years, robotic-assisted choledochotomy and common bile duct exploration (RCD/CBDE) have been introduced as an option for ERCP refractory choledocholithiasis.

Lee et al.[79] reported the experience of robotic surgery for three complicated biliary stone diseases, including large single common bile duct stone, up to 80 stones in a narrow bile duct, and Mirizzi syndrome with polycystic liver. Biliary stones were completely cleaned in all three cases, with no bile leakage observed[79]. Almamar et al.[78] compared RCD/CBDE with open procedures and found that RCD/CBDE had a longer mean duration of surgery (205 ± 70 min vs. 174 ± 73 min, p = 0.08). However, the RCD/CBDE group was superior in terms of postoperative complications (22% vs. 56%, p=0.002) and median hospital stay (6 days vs. 12 days, p=0.01), which may led to lower overall hospital costs ($8449.88 CAD vs. $11671.2 CAD)[78]. Nonetheless, there is a lack of studies comparing the outcomes of RCD/CBDE with LCBDE and ERCP.

For hepatolithiasis, an atrophic liver segment or lobe, or lobe- or segment-predominant disease is considered an indication for surgery[80]. In a study comparing the effects of RLR and OLR in the treatment of hepatolithiasis, the RLR group had significantly less blood loss and shorter hospital stays[80]. Long-term follow-up showed no differences in residual stone rate, recurrent stone rate, or rate of recurrent cholangitis in the two groups[80]. However, the median follow-up time in the RLR group was 19.4 months, and longer follow-up is still needed to clarify the long-term outcomes[80]. In summary, the robotic system offers potential advantages for complicated cholelithiasis, but high-quality prospective studies are still required.

Robotic Extended Cholecystectomy

Biliary system tumors include gallbladder cancer (GBC) and cholangiocarcinoma. For patients with early-stage GBC (Tis or T1a), simple cholecystectomy can achieve a 5-year overall survival rate of 100%[81]. For patients with T1b and later-stage GBC, extended cholecystectomy (EC) is required for radical resection[81]. REC consists of a cholecystectomy, partial hepatectomy, and regional lymph node dissection[81]. Robotic extended cholecystectomy (REC) was not inferior to open extended cholecystectomy (OEC) for GBC in terms of EBL, postoperative complication rate, mortality, number of retrieved lymph nodes, and R0 resection rate[82-84]. Cho et al.[84] reported that the REC had significantly lower EBL (382.7 vs. 717.2 mL, P = 0.020) and LOS (6.9 vs. 8.5 days, P = 0.042) than OEC. Compared with OEC, REC was also associated with less postoperative pain, faster recovery, and shorter LOS[84], although the hospital cost was significantly higher[85].

Researches comparing the effects of REC with laparoscopic extended cholecystectomy (LEC) for GBC are extremely limited. A recent multicenter PSM study showed that LEC had a longer mean operative time (251.5 minutes vs. 196.9 minutes, p=0.010), higher open conversion rate (13.6% vs. 0.0%, p=0.073), and a significantly higher mean hospitalization cost than REC group ($8478 vs $15791, p<0.001)[86]. The two groups had no significant differences in EBL, LOS, severe complication rates, RFS, and OS [86]. Compared with the limited benefits of simple cholecystectomy, robotic surgery seems to offer advantages in EC[87]. The robotic system is suited for delicate dissection in a narrow space, which is helpful in partial liver resection and lymph node dissection during EC[87].

Robotic Radical Surgery for Cholangiocarcinoma

Cholangiocarcinoma can be classified into iCC, hilar cholangiocarcinoma (hCC) and distal cholangiocarcinoma (dCC). Radical surgery for cholangiocarcinoma involves bile duct resection and reconstruction, partial or major hepatectomy, and lymph node dissection[88]. Vascular reconstruction and pancreaticoduodenectomy are sometimes necessary to ensure a negative margin[88].

A systematic review reported that in robotic operation for cholangiocarcinoma, the weighted average operative time was 401 minutes, the EBL was 348 ml, the conversion rate was 7%, the all-cause morbidity was 52%, the major complication rate was 12%, the perioperative mortality was 1.4%, the LOS was 15 days, the positive margin rate was 27%, and number of lymph nodes retrieved was 4.2[88]. These outcomes are comparable to international benchmarks for cholangiocarcinoma[88]. Sucandy et al.[89] prospectively analyzed patients undergoing robotic resection for hCC at three high-volume centers. Among the 38 patients, three required vascular reconstruction[89]. One patient died within 30 days due to a colonic anastomotic leak from a left hemicolectomy performed simultaneously with the hCC resection[89]. After a median follow-up of 15 months, 68% of patients were alive without disease, 13% recurred, and 19% died[89]. These researches demonstrated the safety of robotic surgery for cholangiocarcinoma.

As mentioned above, robotic surgery and open surgery have comparable survival outcomes for iCC. In hCC, Xu et al.[90]

compared the effects of 10 robotic radical resections with those of 32 open radical resections. The robotic group had inferior operation time (703±62 vs. 475±121 minutes, p<0.001), morbidity (90% vs. 50%, p=0.031), and RFS (p=0.029) to the open group, and the hospitalization expenditure was much higher[90]. However, Xu et al.[90] also admitted that this result may be related to the surgeons' inexperience in the early phase of the learning curve.

Pancreaticoduodenectomy (PD) is the only potentially curative treatment for resectable dCC[91]. A multicenter PSM study showed that robotic PD (RPD) was comparable to open PD (OPD) for the treatment of dCC in terms of lymph node harvest, R0 resection, and long-term survival[91]. A study that included 478 patients after PD for dCC demonstrated no significant differences between minimally invasive PD and OPD in terms of the median OS (30 vs. 25 months) and disease-free interval (DFI, 29 vs. 18 months)[92]. In subgroup analysis, RPD had a higher lymph node yield (18.0 vs. 13.5, P=0.008) and less major morbidity (8.1% vs. 32.1%, P=0.005) compared with laparoscopic PD (LPD), with no significant difference in long-term survival outcomes[92]. For biliary system tumors, robotic surgery has advantages in the number of lymph nodes yielded compared with open and laparoscopic surgery[93]. While the impact of these advantages on survival effects remains inconclusive, the promising short-term outcomes suggest that robotic surgery holds good potential for application in biliary system tumors.

Learning Curve

Studies on the learning curve of robotic hepatobiliary surgery are highly heterogeneous. Common learning curve evaluation variables are operation time and blood loss. After approximately 30-40 patients, the operation time and EBL of robotic major hepatectomy[94, 95] and minor hepatectomy (<3 liver segments)[96] are significantly improved. The learning curve of robotic major hepatectomy appears longer than minor resections[97, 98]. Additionally, robotic right hepatectomy's learning curve is longer than left hepatectomy[95, 99].

Compared with LLR, fewer cases are required to overcome the learning curve for RLR[100, 101]. In a systematic review by Chua et al.[100] the median overall number of procedures required for the learning curve of LLR was 50 (range 25-58), and for RLR was 25 (16-50). Although robotic surgery is an extension of laparoscopic surgery, the experience in LLR might not be a necessary pre-requisite to robotic liver surgery[102]. A multicenter retrospective study in the Netherlands showed that the learning curve of RLR in centers with previous laparoscopic liver surgery experience had only two fewer cases compared with centers without experience in laparoscopic liver surgery (33 cases vs 35 cases)[97].

For robotic cholecystectomy, early research reported that the operative time of RC can be significantly shortened in the stage of 16-32 patients[103]. As the number of RC procedures increases, more recent findings by Kudsi et al.[104] suggest that the inflection points for a notable reduction in skin-to-skin time occur at the 84th and 134th cases. Due to the risk of bile duct injury, RC is unsuitable for early training of robotic systems despite its relatively simple procedure[69, 105].

Limitations and Prospects

The adoption of robotic operations in hepatobiliary surgery is increasing, but the robotic system has certain limitations. One major drawback is the lack of specialized instruments, particularly for liver surgery. Instruments such as the harmonic scalpel, cavitron ultrasonic surgical aspirator (CUSA), and water Jet are valuable for liver parenchymal transection and reduction of bleeding in liver procedures[106]. CUSA can clearly expose duct and vessel structures in laparoscopic surgery, but has not been integrated into the robotic system. While the harmonic scalpel has been integrated, it does not possess the full degrees of freedom of other robotic instruments[107].

Another limiting factor of robotic surgery is the lack of a natural sense of touch, which may be detrimental to accurately identifying lesions[108]. Intraoperative ultrasound can be used to investigate liver anatomy and tumor location, and to plan transection lines and margins[109]. However, the robotic system still lacks integrated ultrasound instruments, and laparoscopic ultrasound instruments can conflict with robotic arms. Indocyanine green (ICG) fluorescence imaging was also introduced as an alternative. ICG was used to mark lesions[110], intraoperative bile duct, and blood flow imaging[110]. In hepatobiliary, ICG was shown to shorten operation time, reduce resection volume, improve R0 resection rate, and reduce bile duct injury[110, 111]. Enhanced tactile feedback mechanisms are still under development[108].

In addition, most studies suggest that robotic surgery is associated with higher costs, particularly when compared with laparoscopic surgery[59, 112, 113]. However, robotic surgery is expected to reduce postoperative costs by improving clinical outcomes[39]. Ingallinella et al.[114] reported that postoperative costs were significantly lower in the robotic group for major and posterosuperior hepatectomy (-56.0% vs. open group, -29.4% vs. laparoscopic group, P < 0.001). Robotic surgery offered an advantage over open surgery in terms of total cost (10,637 euros vs 13,960 euros) [114]. The emergence of new competitors in the robotic market is expected to drive down further the prices of robotic systems and consumables[115], thereby reducing intraoperative costs.

It is worth noting that most of the published studies on robotic hepatobiliary surgery are observational studies. Multi-center RCTs are needed to clarify the safety and effectiveness of RLS. Additionally, internationally recognized benchmark values for various robotic hepatobiliary procedures have yet to be defined. Such benchmarks would provide a reference standard for technical learning and offer a reliable basis for comparing outcomes across different populations and surgical approaches.

Conclusions

Nearly 40 years of practice have demonstrated that experienced surgeons can safely perform various robotic hepatobiliary procedures. Robotic systems offer the advantages of 3D visualization, greater flexibility, and tremor filtration. RS may have better short-term outcomes in surgeries with narrow operating spaces or complex anatomical structures (such as posterosuperior hepatectomy). However, in simple cholecystectomy, RS has failed to show a clear advantage over LC. Robotic surgery has also achieved comparable long-term and oncological outcomes to open or laparoscopic surgery. Robotic hepatobiliary surgery still has certain limitations, and multi-center RCTs are needed to clarify its safety and effects, as well as to determine internationally recognized benchmark values.

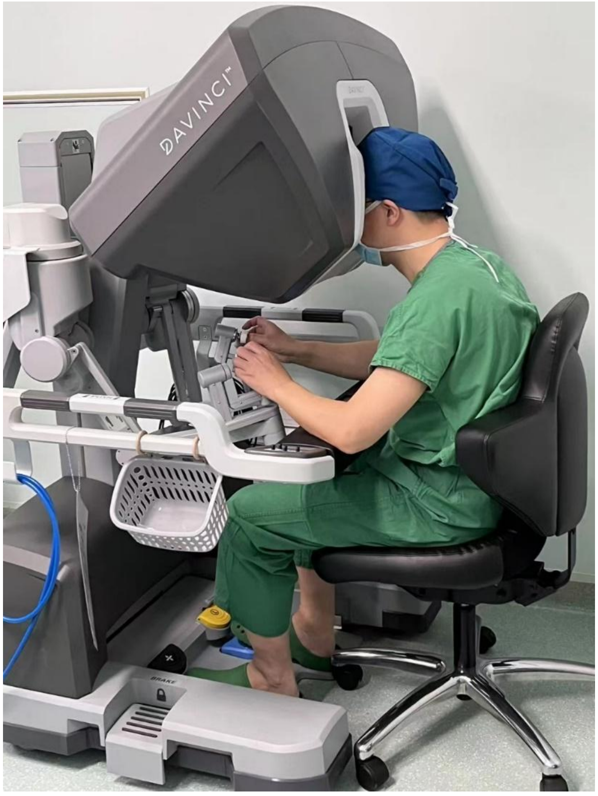

Figure 1. The surgical console

Figure 2. Application of robotic surgery system in liver surgery

Table 1. Comparative study of RLS and LLS or OLS in short-term outcomes

Author	Group	Total	EBL[a], ml	Operative time[a], min	Conversion, n (%)	Complications, n (%)	Postoperative LOS[a], days	90-day mortality, n (%)
Zhang et al.[28] 2024	RLS OLS	280 465	*200 (100-300) *400 (200-800)	*181 (130－230) *201 (180-245)	NA	*6 (2%) *28 (6%)	*6 (5-8) *9 (8-12)	NA NA
Sucandy et al.[38] 2022	RLS OLS	42 42	*200 (239 ± 183.6) *300 (491 ± 577.1)	293 (302±131.5) 280 (300±115.6)	NA	2 (4.8%) 7 (16.7%)	*4 (4±3.3) *6 (6±2.7)	1 (2.4%) 3 (7.1%)
Benedetto et al.[39] 2023	RLS OLS	106 106	*200 (100-500) *100(100-150)	*295 (190-370) *200 (165-255)	NA	3 (2.8%) 12 (11.3%)	*4 (3-6) *10 (7-13)	
Li et al.[37] 2024	RLS LLS	97 244	100 (50-300) 100 (50-300)	*210.0 (152.0-298.0) *183.50 (132.25-263.50)	2 (2.1%) 18 (7.4%)	4 (4.1%) 21 (8.6%)	8 (7-9) 8 (7-10)	0 0
Tsung et al.[40] 2014	RLS LLS	57 114	200 (50-337.5) 100 (50-350)	*253 (180-355) *198.5 (137.75-261.5)	4 (7%) 10 (8.8%)	11 (19%) 8 (8.5%)	4.0 (3.0-5.5) 4.0 (3.0-5.0)	0 2 (1.8%)
Lai et al.[47] 2016	RLS LLS	100 35	224.5 (5-3500) 336.0 (5-2000)	*207.4±77.1 *134.2±41.7	4 (4%) 2 (5.7%)	14(14%) 7 (20%)	7.3±5.3 7.1±2.6	0 0
Liu et al.[48] 2023	RLS LLS	841 841	*200.0 (100.0-450.0) *300.0 (150.0-500.0)	292.0 (225.0-400.0) 300.0 (234.5-390.0)	*43 (5.1%) *100 (11.9%)	199 (23.7%) 212 (25.2%)	*6.1 (4.3-9.0) *7.0 (5.0-9.0)	7 (0.8%) 15 (1.8%)
Yoshino et al.[49] 2023	RLS LLS	39 32	550 (200-1000) 475 (300-825)	249 (197-296) 222 (183-280)	*1 (2.6%) *10 (31.3%)	NA	*4 (3-7) *6 (4-8.5)	5 (12.8%) 2 (6.3%)
Sucandy et al.[50] 2022	RLS LLS	164 164	*100 (NA) *200 (NA)	273.5 (NA) 273.5 (NA)	*4 (2.4%) *13 (7.9%)	*26 (15.9%) *27 (16.5%)	*6 *7	2 (1.2%) 3 (1.8%)
Chong et al.[51] 2022	RLS LLS	220 220	300.00 (100.00-600.00) 300.00 (186.00-500.00)	315.00 (241.50-461.25) 346.50 (260.00-452.00)	*19 (8.6%) *39 (17.7%)	68 (30.9%) 70 (31.8%)	7.00 (5.00-10.00) 7.00 (5.00-10.00)	6 (2.7%) 1 (0.5%)
Sijberden et al.[52] 2024	RLS LLS	1505 1505	*100 (50-280) *200 (100-400)	190 (139-272) 210 (136.3-300)	*39 (2.7%) *130 (8.8%)	*291 (19.3%) *384 (25.7%)	4 (3-6) 4 (3-6)	23 (1.5%) 21 (1/4%)
Krenzien et al.[54] 2024	RLS LLS	449 449	*100.00 (50.00-200.00) *163.00 (50.00-300.00)	*225.00 (160.00-303.75) *188.00 (140.00-270.00)	*23 (5.1%) *10 (2.2%)	74 (16.5%) 91 (20.3%)	*5.00 (4.00-8.00) *5.00 (3.00-6.00)	2 (0.4%) 1 (0.2%)
D'Silva et al.[57] 2022	RLS LLS	159 824	*100 (50-200) *200 (50-450)	*184 (135-277) *210 (150-293)	%1 (0.6%) %56 (6.8%)	28 (17.6%) 145 (17.6%)	*5 (3-6) *5 (3-7)	1 (0.6%) 6 (0.7%)
Salloum et al.[58] 2017	RLS LLS	16 80	247±239 206±205	190±87 162±51	2 (13%) 2 (3%)	2 (13%) 9 (11%)	6±4 7±8	0 1 (1%)
Hu et al.[59]	RLS LLS	58 54	80.1±144.4 108.9±180.8	107.0±45.2 95.7±47.5	0 1 (1.9%)	1 (1.7%) 2 (3.7%)	4.3±1.8 4.4±1.8	0 0

2019								
Zhu et	RLS	56	200 (10-1500)	*220 (85-595)b	8 (14.3%)	7 (12.5)	*6 (3-48)b	0
al.[60]	LLS	56	200 (10-1600)	*215 (85-505)b	7 (12.5%)	10 (17.9%)	*8 (4-23)b	0
2023	OLS	56	200 (50-1000)	*155 (70-325)b	NA	13 (23.2%)	*12 (7-23)b	0
Cheung et	RLS	73	200 (100-500)	242 (197-359)	6 (8.2%)	21 (28.8%)	6 (4-9)	0
al.[61]	LLS	219	300 (110-500)	290 (210-360)	24 (11%)	48 (21.9%)	6 (4-7)	6 (2.7%)
2023								

aData are presented as median (interquartile range) or mean (±standard deviation).
bIndicates statistical significance when compared with OLS.
RLS, robotic liver surgery; OLS, open liver surgery; LLS, laparoscopic liver surgery; EBL, estimated blood loss; LOS, length of stay; NA, not available; *, Statistically significant (P value＜0.05).

Table 2. Comparative study of RLS and LLS or OLS in long-term and oncological outcomes

Author	Group	Total	OS[a]	RFS[a]	DFS[a]	R0 resection, n (%)
Zhang et al.[28]	RLS	280	68.9 (55.1-NA)	25.7 (16.7-31.3)	NA	NA
2024	OLS	465	64.4 (56.0-79.0)	20.0 (15.2-23.8)		
Sucandy et al.[38]	RLS	42	*38.499 (NA)	NA	NA	33 (85%)
2022	OLS	42	*26.367 (NA)			38 (93%)
Zhang et al.[66]	RLS	100	52.8 (NA)	20.4 (NA)	NA	NA
2022	OLS	178	57.6 (NA)	24.6 (NA)		
Li et al.[37]	RLS	97	74.8% (65.4-85.6%)	*65 (NA)	NA	96 (99%)
2024	LLS	244	80.7% (48.6-70.6%)	*56 (NA)		234 (95.9%)
Lai et al.[47]	RLS	100	NA	NA	NA	96 (96%)
2016	LLS	35				32 (91.4%)
Zhu et al.[60]	RLS	56	78.6% (NA)	NA	51.8%	55 (98.2%)
2023	LLS	56	76.8% (NA)		51.3%	54 (96.4%)
	OLS	56	74.4% (NA)		57.9%	56 (100%)

aSurvival data are presented as median (months, 95% confidence interval) or 5-year rate (%, 95% confidence interval).
RLS, robotic liver surgery; OLS, open liver surgery; LLS, laparoscopic liver surgery; OS, overall survival; RFS, recurrence-free survival; DFS, disease-free survival; NA, not available; *, Statistically significant (P＜0.05).

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Competing interest

The authors declare no conflicts of interest in this work.

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