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Robotic-assisted laparoscopic surgery for complex hepatolithiasis: a propensity score matching analysis

Jie Shu[1] · Xiao-jun Wang[1] · Jian-wei Li[1] · Ping Bie[1] · Jian Chen[1] · Shu-guo Zheng[1]

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Abstract

Background The indication for laparoscopic treatment of hepatolithiasis is early-stage regional hepatolithiasis. Open surgery (OS) is the traditional treatment for complex hepatolithiasis. Robotic-assisted laparoscopic surgery (RLS) overcomes the limitations of the traditional laparoscopic approach in terms of the visual field, instruments, and operational flexibility. RLS is thus theoretically indicated for the treatment of complicated hepatolithiasis. This study aimed to evaluate the safety, efficacy, and feasibility of RLS for the treatment of complicated hepatolithiasis.

Methods From October 2010 to August 2017, 26 consecutive patients who underwent RLS and 287 consecutive patients who underwent OS for the treatment of complicated hepatolithiasis at our center were included in this study. We performed a propensity score matching (PSM) analysis between patients who underwent RLS and patients who underwent OS at a ratio of 1:2. Twenty-six patients were included in the RLS group, and 52 patients were included in the OS group.

Results The groups exhibited no differences with respect to age, sex, location of stones, liver function, history of previous surgery, or Child–Pugh classification. There were no differences in the postoperative complication rates (46.2% vs. 63.5%, $p=0.145$), intraoperative stone clearance rates (96.2% vs. 90.4%, $p=1.000$), or final stone clearance rates (100% vs. 98.1%, $p=0.652$) between the two groups. The RLS group had less blood loss (315.38 ± 237.81 vs. 542.88 ± 518.70 ml, $p=0.037$), a lower transfusion rate (15.4% vs. 46.2%, $p=0.008$), shorter oral intake times (3.50 ± 1.30 vs. 5.88 ± 4.00 days, $p=0.004$), and shorter postoperative hospital stays (13.54 ± 6.54 vs. 17.81 ± 7.49 days, $p=0.016$) than the OS group. At a median follow-up of 48 months (range 7–90 months), there were no differences in stone recurrence rate (3.8% vs. 13.5%, $p=0.356$) or recurrent cholangitis rate (3.8% vs. 3.8%, $p=1.000$) between RLS and OS patients.

Conclusion RLS for complicated hepatolithiasis is safe and feasible with advantages over OS in terms of intraoperative blood loss, transfusion rate, duration of hospital stays, and postoperative recovery.

Keywords Robotic · Minimally invasive surgery · Laparoscopy · Hepatolithiasis · Liver resection · PSM

Hepatolithiasis is prevalent in Southeast Asian countries, especially in the southern and southwestern districts of China, but is rare in western countries. It has been reported that the relative prevalence of hepatolithiasis is as high as 20% [1]. Nonetheless, with the rapid increase in immigrants, the prevalence of hepatolithiasis in western countries is rising, with a reported incidence of 0.6–1.3% [2, 3]. Long-term hepatolithiasis can lead to biliary cirrhosis, biliary portal hypertension, and even cholangiocarcinoma, which is lethal and imposes a large burden on society. The treatment aims for hepatolithiasis are to resect all non-functional hepatic lobes with diseased lesions, to remove all biliary stones, to correct bile duct strictures, to establish ample drainage of the obstructed biliary system and to prevent the recurrence of bile duct stones [4–6]. Surgery is currently the primary method used to manage hepatolithiasis, but the postoperative residual stone rate and the reoperation rate are high. Traditional open surgery (OS) is the classic approach for the treatment of hepatolithiasis. However, there are many

Jie Shu and Xiao-jun Wang have contributed equally to this work.

✉ Shu-guo Zheng
shuguozh@163.com

Jie Shu
shujiecn@163.com

[1] Institute of Hepatobiliary Surgery, Southwest Hospital, Third Military Medical University (Army Medical University), 30 Gaotanyan Main Street, Shapingba District, Chongqing 400038, China

disadvantages to OS, such as substantial surgical trauma, destruction of the integrity of the abdominal wall, a high rate of incision infection, slow postoperative recovery, and reoperation difficulty. In recent years, improvements in laparoscopic techniques and devices have made minimally invasive surgery possible for the treatment of intrahepatic bile duct stones. Both reports in the literature and our studies have suggested that laparoscopic hepatectomy combined with choledochoscopy exploration for the treatment of hepatolithiasis is safe and feasible in selected cases and yields satisfactory results [7, 8]. However, the published cases primarily involved early-stage regional hepatolithiasis or hepatolithiasis limited to the left liver lobe. Due to limited laparoscopic vision and poor instrumental stability and flexibility, fine anatomical dissection and separation of the porta hepatis and hepatoduodenal ligaments are difficult. These deficiencies limit the further application of laparoscopic procedures to delicate and complex surgeries. Severe repeated cholangitis in patients with hepatolithiasis indicates that cholangitis is usually associated with hilar bile duct stenosis, atrophy of the infected liver segments, and hepatic hilar translocation. Furthermore, severe adhesions in the first porta hepatis that emerge after one or more operations, anatomical variations, and other factors make laparoscopic surgery difficult to implement. Therefore, complex hepatolithiasis has usually been regarded as a contraindication for laparoscopic procedures, and OS has remained the standard treatment. Complicated hepatolithiasis is characterized as follows: (1) combined with hepatic hilar bile duct stricture requiring bile duct plastic surgery and reconstruction; (2) combined with hepatic atrophy–hyperplasia syndrome leading to hepatic hilar translocation; and (3) a history of previous surgeries with severe adhesions in the hepatic hilum that require biliary tract surgery combined with hepatectomy [9–11].

In recent years, robotic surgical systems have been applied to a variety of hepatobiliary and pancreatic surgical procedures, including major hepatectomy, radical resection of hilar cholangiocarcinoma, biliary reconstruction, and pancreatoduodenectomy [12–14]. Robotic surgical systems provide three-dimensional (3D) vision and internal wrist devices, which proportionally reduce the range of movement of manual operations. They also eliminate the physiological vibration of human hands and improve the stability of the operation and the precision of the surgery, overcoming the limitations of laparoscopic techniques. In addition, robotic surgical systems are suitable for manipulation and fine dissection in confined surgical fields. Regarding the successful use of surgical robots for living donor liver transplantation and hilar cholangiocarcinoma resection, removal of complex hepatobiliary stones with hilar bile duct lesions has been speculated to be a promising application of robotic surgical systems [15]; however, few studies have reported the safety and feasibility of robotic surgical systems for the treatment of complicated hepatolithiasis. We retrospectively analyzed the clinical data of 26 patients with complex intrahepatic bile duct stones treated with robotic-assisted laparoscopic surgery (RLS). To reduce the confounding bias, a 1:2 propensity score matching (PSM) analysis was conducted based on the age, sex, liver function tests, Child–Pugh classification, history of previous surgery, and the location of stones between patients in the RLS and OS groups. The perioperative data and follow-up results were observed, providing more clinical evidence for the safety, feasibility, and effectiveness of robotic surgical systems for the treatment of complex hepatolithiasis.

Materials and methods

Inclusion criteria

The inclusion criteria were as follows: (1) the patient was a candidate for the administration of anesthesia and for hepatectomy according to his/her general condition; (2) an indocyanine green retention rate at 15 min (ICG R15) $< 10\%$, with a ratio of residual liver volume to standard liver volume $> 40\%$ for patients who had undergone liver resection; (3) Child–Pugh class A or B liver function; and (4) a definitive diagnosis of complicated hepatolithiasis before the operation, including characteristics such as hilar bile duct stricture, anticipated hepatic hilar bile duct plasty or biliary reconstruction, atrophy–hyperplasia complex or hilar translocation, severe adhesions in the porta hepatis, and reoperation of the biliary tract.

Patient information

This study was approved by the Ethics Committee of the First Affiliated Hospital of Third Military Medical University (Army Medical University). From October 2010 to August 2017, 26 consecutive patients who underwent RLS for the treatment of complicated hepatolithiasis at our institute and met the above inclusion criteria were analyzed. During the same period, 287 patients who underwent OS for complex hepatolithiasis were also included.

There was only one robotic surgical system in our hospital. Our department has a fixed day for robotic surgery each week, as other departments also use the robotic system. Some of the high equipment costs are not reimbursed by medical insurance. The start-up costs associated with the robotic system and the cost of disposable high-value consumables are borne by the patients who undergo robotic surgery. For these reasons, some patients with hepatolithiasis who were suitable candidates for robotic surgery selected to undergo OS. However, all patients in our research study met the same inclusion criteria, and they were all suitable for both open and robotic surgery.

To reduce confounding bias, the PSM [16, 17] method was conducted. A logistic regression model was built in which age, sex, history of previous surgery, stone distribution, liver cirrhosis, liver function test results, and Child–Pugh classification were independent variables, and the operation mode (1 = RLS; 0 = OS) was the dependent variable. R software was used to calculate the propensity score (PS) values for 313 patients, and 26 patients who underwent RLS were matched successfully with 52 patients who underwent OS through the nearest neighbor matching method, maintaining a ratio of 1:2. The OS group comprised 52 patients. Informed consent for the surgical operation was obtained from each patient.

Routine blood tests, liver and kidney function tests, coagulation function tests, electrolyte tests, and other laboratory examinations were performed before the operation. Chest CT scans and arterial blood gas analyses were routinely performed to determine the respiratory condition of the patients, and ECG and/or echocardiography were used to assess cardiac function. The levels of tumor markers were also detected. Abdominal ultrasound, abdominal computed tomography angiography (CTA), and magnetic resonance cholangiopancreatography (MRCP) were performed to confirm the location of the stones and vascular deviations; if necessary, endoscopic retrograde cholangiopancreatography (ERCP) or percutaneous transhepatic biliary drainage (PTBD) were used to reduce jaundice. In patients undergoing hepatectomy, ICGR15 was performed, and the ratio of the future remnant hepatic volume to the standard hepatic volume was calculated according to CTA. In more recent cases, 3D imaging was applied to display the morphology of the intrahepatic bile ducts, especially for patients with biliary stricture of the affected liver segments; the location of the stones and anatomic variations; and the relationship between the bile duct system and major vessels. In total, 3D imaging was performed for 3 patients and 12 patients in the RLS and OS groups, respectively.

Operative techniques

Preoperative preparation: prophylactic antibiotics were administered 30 min before the induction of anesthesia and continued for 5–7 days postoperatively according to the postoperative laboratory test results. Gastric tubes and urinary catheters were routinely placed before the operation.

In the RLS group, patients were supine in a 30° reverse Trendelenburg position under intravenous–inhalation combined anesthesia. The patients' legs were spread apart. CO_2 pneumoperitoneum was established by a Veress needle above the umbilicus, and the intraabdominal pressure was set to 12–14 mmHg. Pneumoperitoneum was established by means of an open incision in patients with a history of previous surgery, and the Veress needle was inserted more than 5 cm from the original incision.

The abdominal cavity was explored upon placing the robotic camera into the umbilical trocar. Three 8-mm trocars as robotic arms and one 12 mm trocar as an assistant port were inserted under direct vision with the robotic camera. The distance between each trocar was approximately 8–10 cm. The trocars were placed in a fan shape around the lesion location and the main surgical site. The position of trocar insertion varied slightly for different surgical approaches. During the operation, the robotic arms I and II were the main manipulators, while arm III was used for retraction. The robotic system was brought into position over the patient's head and docked after placement of the trocars. The surgeon operated the robot console, while the assistant remained over the patient's legs and operated the suction, clamps and scissors. The assistant also performed intraoperative ultrasound and choledochoscopy and completed procedures involving traction, pulling, delivery, stapling and changing the robotic instruments as the operation progressed. A T-tube was selectively inserted through the suitable trocar incision after surgery. Abdominal exploration was first performed to determine whether there were lesions on other organs. Intraoperative laparoscopic ultrasound exploration was used to determine the location of the stones and to identify diseased bile ducts. The liver parenchymal transection plane was determined based on the preoperative imaging and intraoperative ultrasonography data. The ischemic demarcation was indicated on the liver surface using electrocoagulation.

The procedure was divided into five stages. (1) Abdomen adhesiolysis. First, the adhesions among the liver, stomach, intestine, omentum, other tissues, organs, and abdominal wall were separated. Then, adhesions of the visceral side of the liver with the stomach, colon, duodenum, omentum and other tissues were divided and dissected. Attention was paid to identifying gaps in inflammatory tissue. Both blunt and sharp dissection were used during adhesiolysis. It was important to ensure appropriate dissection and prevent injury to the colon, duodenum, and stomach. The hepatoduodenal ligament and the hepatic hilum were fully exposed for further operation. (2) Dissection of the porta hepatis. Depending on the type of hepatectomy, the hepatic arteries, portal veins, and biliary branches of the liver segments being resected were dissected through intracapsular or extracapsular transection of the Glisson pedicle. Patients with hepatolithiasis usually underwent intracapsular anatomical separation because of the presence of stones, dilatation, strictures, and variation in the hilar bile duct. (3) Liver mobilization and transection of the hepatic parenchyma. For left hepatectomy, the round, falciform, left triangular, and left coronary ligaments were divided with a harmonic scalpel (Ethicon

Endo-surgery, USA) or an electronic cautery hook, and then, the roots of the left hepatic vein and the middle hepatic vein were exposed. For right hepatectomy, the right coronary, triangular, and hepatorenal ligaments were separated, and the root of the right hepatic vein was exposed. The inferior vena cava (IVA) was exposed from a caudal to cephalic direction up to the root of the hepatic vein. The small branches of the IVA were clamped with titanium clips or a Hem-o-lock, and the larger branches were sutured with Prolene sutures. Liver transection was carried out using a harmonic scalpel. An intermittent Pringle maneuver was used if necessary. Blood inflow was blocked for 10 min each time at an interval of 5 min. Central venous pressure (CVP) was maintained at 2–4 cm H_2O to minimize additional blood loss from the hepatic vein. Errhysis and bile leakage of small elements were occluded by bipolar electrocautery, a BiClamp (Erbe China Ltd.), or suturing with Prolene, if necessary. Vessels smaller than 3 mm in diameter were divided with a harmonic scalpel; vessels between 3 and 7 mm in diameter were ligated with titanium clips, a Hem-o-lock or absorbable biological clamps; and vessels larger than 7 mm in diameter were controlled using an endoscopic linear cutter and reloads (ECHELON 45/60 ENDOPATH Stapler, USA). If bleeding was difficult to control, conversion to laparotomy was necessary. A surgical absorbable hemostat was used selectively on the raw surface of the resected liver. The resected specimen was placed in a specimen bag, disintegrated, and retrieved through an enlarged abdominal incision. (4) Choledochoscopy exploration and removal of stones. For patients with multiple stones and cystic dilatation, atrophy of the bile duct, liver atrophy and hepatic fibrosis, segmentectomy, lobectomy, or hemihepatectomy may be effective for the thorough removal of the liver lesion. A choledochoscope was used to explore the intrahepatic and extrahepatic bile ducts, and the residual bile duct stones were removed by basket, forceps, or saline flushing. (5) Bile duct plasty and biliary reconstruction. The strictures of the bile duct were fully exposed in patients with hilar bile duct stenosis. Hepaticojejunostomy was performed after the orifice of the ducts was enlarged. For patients with duodenal sphincter of Oddi dysfunction, Roux-en-Y cholangiojejunostomy was performed after transection of the common bile duct. An abdominal drainage tube was routinely placed.

Patients in the OS group underwent the same anesthesia protocol as those in the RLS group. In the OS group, an oblique incision was usually made along the right costal margin upper to the sword and right midaxillary line depending on the lesion position and the operation site. After the abdominal incision was made, the adhesions around the liver were first separated, and then, the first porta hepatis was dissected. Intraoperative ultrasound was used to identify stones and the landmark hepatic veins. Hepatic parenchyma transection was implemented by the traditional clamping method. The Pringle maneuver was carried out to occlude blood inflow to the liver if necessary. The duration of occlusion was 10 min, and the duration of open blood inflow was 5 min. Stones were removed with forceps, saline flushing or a spiral extractor basket when the bile duct was opened. Large, stiff stones were broken up by holmium laser lithotripsy. Biliary tract exploration with choledochoscopy was performed to confirm the presence of residual stones and bile duct stenosis. In cases of hilar bile duct stenosis, bile duct plasty was performed, and Roux-en-Y anastomosis was used to ensure bile drainage. A T-tube and an abdominal drainage tube were routinely placed after removal of the liver specimen. Both groups received the same postoperative treatment, including administration of antibiotics, rehabilitation procedures, retesting of liver and kidney function, coagulation function and electrolyte levels, and repeated abdominal ultrasounds.

Follow-up

Patients in both groups underwent regular postoperative follow-up in the outpatient department at 3 months after surgery and then once by telephone or as outpatients every 6 months at the Clinical Research Center of the Institute of Hepatobiliary Surgery of the First Affiliated Hospital of Third Military Medical University (Army Medical University). All patients underwent routine blood tests, liver function tests, and abdominal ultrasound. CT and/or MRCP examinations were carried out in patients suspected of having residual bile duct stones or recurrent cholangitis.

Statistical analysis

IBM SPSS Statistics 24.0 and R software 3.4.3 were used to perform the statistical analyses and PSM, respectively. All values are presented as the mean ± standard deviation (SD). *t* tests were used to compare the means between two groups. Rates were compared using Pearson's Chi-square test with continuity correction or Fisher's exact test. A p value < 0.05 was considered statistically significant. Standardized differences were used to assess the degree of baseline covariate balance between two groups. An accepted degree of balance is reflected by a standardized difference of < 10%. Standardized differences for each baseline variable were calculated in the manner described by Austin [18].

Results

The mean age of the patients in the RLS group was 53 years (range 20–70 years). Nine patients were male, and 17 were female. Twenty-four patients presented with abdominal pain, nine with jaundice, and five with fever. Nineteen patients presented with hilar translocation due to repeated cholangitis, six patients had hilar bile duct stricture, and nine patients required biliary reconstruction. Hypertension and diabetes were prospectively observed in one of these patients. Twenty-four patients were classified as Child–Pugh class A, and two were Child–Pugh class B. Nineteen patients presented with hilar translocation, and nine patients had severe adhesions due to previous biliary surgeries. The demographic data, clinical characteristics and stone distributions of all patients in both groups are listed in Table 1. No significant differences in patient demographics and characteristics were found between the two groups. In the RLS group, nine patients had undergone previous operations, of which seven patients had undergone one previous operation and two patients had undergone two previous operations. In the OS group, 16 patients had undergone previous operations, of which 13 patients had undergone one previous operation, two patients had undergone two previous operations, and one had undergone three operations.

Table 2 lists the operation methods used in both groups. Perioperative and follow-up results are shown in Table 3. Among the 26 patients in the RLS group, only one converted to OS, resulting in a conversion rate of 3.8%. The reason for the conversion was difficultly exposing the severe adhesions around the hepatic hilum. There was no significant difference in the operation method between the groups. The RLS group had less blood loss, a lower blood transfusion rate, faster postoperative recovery, and a shorter postoperative hospital stay than the OS group. In contrast, the RLS group had longer operation times and greater total hospitalization costs than the OS group. There were no significant differences between the groups in the intraoperative calculi clearance rate, the postoperative complications rate, the rate of stone recurrence, and the rate of cholangitis recurrence. In the RLS group, stones were successfully removed from 25 of the 26 patients, and the remaining stones were removed via the T-tube tract 6 weeks after the operation. The final stone clearance rates were 100% and 98% in the RLS and OS groups, respectively. The overall complication rates in the RLS and OS groups were 46.2% and 65.4%, respectively. The complications were classified according to the 2004 revised version of the Clavien–Dindo surgical complications classification [19]. One patient in the RLS group and three patients in the OS group with pleural effusion were cured after thoracic puncture and drainage. Three patients in the RLS group and six in the OS group required abdominal puncture and drainage due to bile leakage (two in the RLS group and five in the OS group) and raw surface effusion (one in the RLS and one in the OS group). One patient in the OS group required reoperation due to postoperative bleeding from the stump of the left hepatic artery on postoperative day 9. One patient in the OS group developed type I respiratory failure on day 6 postoperatively. The patient's condition was improved by endotracheal intubation with assisted respiration in the intensive care unit, and the patient was successfully weaned from the ventilator 5 days later. All patients with complications showed improvement at the time of discharge, except for two patients, whom died postoperatively. One patient was a 73-year-old woman who exhibited left intrahepatic duct stones and underwent left hepatectomy with biliary exploration and Roux-en-Y cholangiojejunostomy. She developed a postoperative incisional hernia and intestinal necrosis and underwent reoperation with small bowel resection and anastomosis 5 days after the initial surgery. She died from sepsis and malnutrition after repeat surgery at 99 days postoperatively. The other patient was a 54-year-old female who had intrahepatic duct and common bile duct stones. She underwent hepatectomy in segment III with bile duct exploration and Roux-en-Y cholangiojejunostomy and developed postoperative intraabdominal hemorrhage. She died of hemorrhagic shock 5 days after surgery. The complications are listed in Table 4.

Seventy-one patients (91.0%) were successfully followed-up for a median of 48 months (range 7–90 months). One patient in the RLS group had recurrent stones and underwent another operation. One patient had intermittent symptoms of cholangitis, including fever and abdominal pain, which improved after receiving medical treatment. In the OS group, stone recurrence occurred in seven patients, two of whom were treated with repeated surgeries and three of whom were successfully treated by percutaneous transhepatic removal of stones via choledochoscopy exploration. Two patients developed symptoms of cholangitis with abdominal pain and fever that improved after anti-infection treatment. In the RLS group, one patient died of progressive colorectal cancer. One patient in the OS group died of end-stage liver disease and upper gastrointestinal bleeding.

Discussion

Hepatolithiasis is prevalent in the southwestern and southern regions of China. The incidence of complications and the rate of postoperative stone recurrence are high. The principle of treatment for hepatolithiasis is to resect the involved nonfunctional hepatic segments with diseased lesions, remove all the stones, correct all stenoses and establish ample drainage to prevent the recurrence of bile duct stones. A variety of surgical procedures, including bile duct exploration, liver segmentectomy or hepatic lobectomy, plasty of the stenotic bile ducts, and biliary reconstruction such as bilioenteric anastomosis, are often required to achieve these outcomes. Intraoperative choledochoscopy, cholangiography, ultrasound, and other techniques are used to improve the efficacy of surgery. Regarding the long-term effects, anatomical resection of the liver segment(s) containing stones can

Table 1 Patient demographics and clinical characteristics of the RLS and OS groups

	RLS group ($n=26$)	OS group ($n=52$)	p value	Standardized differences
Age (years) (mean, SD)	53.92 ± 11.46	51.77 ± 10.94	0.422	0.192
Sex (%)				
Male	9 (34.6%)	17 (32.7%)	0.865	0.041
Female	17 (65.4%)	35 (67.3%)		
Liver cirrhosis (%)	2 (7.7%)	7 (13.5%)	0.707	− 0.188
Child–Pugh class (%)				
A	24 (92.3%)	48 (92.3%)	1.000	0.000
B	2 (7.7%)	4 (7.7%)		
Albumin (g/l) (mean, SD)	39.88 ± 4.39	40.46 ± 4.95	0.615	− 0.124
Total bilirubin (μmol/l) (mean, SD)	21.75 ± 27.53	20.38 ± 16.92	0.787	0.060
Prothrombin time (s) (mean, SD)	11.82 ± 1.25	11.85 ± 0.93	0.891	0.031
Manifestations (%)				
Abdominal pain	24 (92.3%)	52 (100.0%)	0.205*	− 0.408
Jaundice	9 (34.6%)	9 (17.3%)	0.087	0.403
Fever	5 (19.2%)	10 (19.2%)	1.000	0.000
Comorbidities (%)			1.000*	− 0.052
HBV infection	0 (0.0%)	4 (7.7%)		− 0.408
Hypertension	1 (3.8%)	2 (3.8%)		0.000
Diabetes	1 (3.8%)	2 (3.8%)		0.000
COPD	1 (3.8%)	1 (1.9%)		0.115
Asthma	1 (3.8%)	0 (0.0%)		0.283
Stone locations (%)				
III	1 (3.8%)	1 (1.9%)	0.994	0.115
II + III	3 (11.5%)	7 (13.5%)		− 0.058
II + III + IV	13 (50.0%)	27 (51.9%)		− 0.038
II + III + VI + VII	2 (7.7%)	5 (9.6%)		− 0.068
V + VI + VII + VIII	3 (11.5%)	5 (9.6%)		0.0626
VI + VII	1 (3.8%)	3 (5.8%)		− 0.090
Left lobe + hilum	1 (3.8%)	2 (3.8%)		0.000
Left lobe + caudate lobe	2 (7.7%)	2 (3.8%)		0.166
Combined with gallstones (%)	19 (73.1%)	34 (65.4%)		0.167
Combined with CBD stones (%)	12 (46.2%)	21 (40.4%)		0.116
Number of previous surgeries (%)				
One	7 (26.9%)	13 (25%)	0.855	0.044
Two	2 (7.7%)	2 (3.8%)	0.856*	0.166
Three	0	1 (1.9%)	1.000**	− 0.198
Previous operation (%)				
Cholecystectomy	6 (23.1%)	12 (23.1%)	0.732	0.000
Cholecystectomy + biliary exploration	2 (7.7%)	3 (5.8%)		0.077
Cholecystectomy + biliary reconstruction	1 (3.8%)	1 (1.9%)		0.115
Complex types (%)				
Atrophy–hypertrophy syndrome	19 (73.1%)	35 (67.3%)	0.603	0.126
Hilar bile duct stenosis	6 (23.1%)	17 (32.7%)	0.380	− 0.216
History of previous surgery	9 (34.6%)	16 (30.8%)	0.732	0.082

SD standardized deviation, *RLS* robotic-assisted laparoscopic surgery, *OS* open surgery

*Continuity correction

**Fisher's exact test

Table 2 Surgical procedures of the RLS and OS groups

	RLS group (*n* = 26)	OS group (*n* = 52)	*p* value	Standardized differences
Liver resection (%)				
Left lateral hepatectomy	3 (11.5%)	9 (17.3%)	0.688	−0.165
Left hemihepatectomy	16 (61.5%)	32 (61.5%)		0.000
Right hemihepatectomy	4 (15.4%)	6 (11.5%)		0.113
Right posterior hepatectomy	0 (0.0%)	1 (1.9%)		−0.198
Segmentectomy (346)	2 (7.7%)	4 (7.7%)		0.000
Hilar bile duct plasty and reconstruction alone	1 (3.8%)	0 (0.0%)		0.283
Combined with bile duct reconstruction (%)	6 (23.1%)	17 (32.7%)	0.380	−0.216
Combined with CBD exploration (%)	12 (46.2%)	21 (40.4%)	0.627	0.117

RLS robotic-assisted laparoscopic surgery, *OS* open surgery

Table 3 Perioperative and long-term outcomes of the RLS and OS groups

	RLS group (*n* = 26)	OS group (*n* = 52)	*p* value
Operation time (time) (mean, SD)	376.69 ± 129.05	319.15 ± 127.58	0.065
Blood loss (ml) (mean, SD)	315.38 ± 237.81	542.88 ± 518.70	0.037
Blood transfusion (%)	4 (15.4%)	24 (46.2%)	0.008
Conversion to open surgery (%)	1 (3.8%)	–	–
Oral intake time (days) (mean, SD)	3.50 ± 1.30	5.88 ± 4.00	0.004
Postoperative hospital stays (days) (mean, SD)	13.54 ± 6.54	17.81 ± 7.49	0.016
Costs ($) (mean, SD)	15239.14 ± 4498.92	12172.51 ± 5371.68	0.014
Intraoperative stone clearance (%)	25 (96.2%)	47 (90.4%)	1.000*
Final stone clearance (%)	26 (100%)	51 (98.1%)	0.652*
Stone recurrence (%)	1 (3.8%)	7 (13.5%)	0.356*
Recurrent cholangitis (%)	1 (3.8%)	2 (3.8%)	1.000*

RLS robotic-assisted laparoscopic surgery, *OS* open surgery

*Fisher's exact test

Table 4 Postoperative complications

Clavien–Dindo classification	Complications	RLS group *n* (%)	OS group *n* (%)	*p* value
I	Pleural effusion	1 (3.8%)	1 (1.9%)	
	Raw surface effusion	2 (7.7%)	1 (1.9%)	
	Incision infection	1 (3.8%)	4 (7.7%)	
II	Anemia requiring blood transfusion	0 (0.0%)	4 (7.7%)	
	Pulmonary infection	3 (11.5%)	5 (9.6%)	
	Abdominal infection	1 (3.8%)	3 (5.8%)	
IIIa	Pleural effusion	1 (3.8%)	3 (5.8%)	
	Raw surface effusion	1 (3.8%)	1 (1.9%)	
	Bile leakage	2 (7.7%)	5 (9.6%)	
IIIb	Hemorrhage	0 (0.0%)	2 (3.8%)	
	Incisional hernia and intestinal necrosis	0 (0.0%)	1 (1.9%)	
IV	Respiratory failure	0 (0.0%)	1 (1.9%)	
V	Death	0 (0.0%)	2 (3.8%)	
Total		12 (46.2%)	33 (63.5%)	0.196

RLS robotic-assisted laparoscopic surgery, *OS* open surgery effectively remove residual stones, reducing the incidence of stone recurrence and cholangiocarcinoma. Laparoscopic liver resection provides a minimally invasive treatment approach for early regional hepatolithiasis [8, 15]. However, laparoscopic surgery is difficult for complicated hepatobiliary stones with obvious atrophy–hyperplasia complex, hepatic hilar translocation, and hilar bile duct stenosis. Currently, these diseases are still generally treated by OS [20]. However, after repeated abdominal laparotomies, patients often suffer marked abdominal pain, delayed postoperative ambulation, and difficulty in expectoration. These patients are also prone to lung infections, and elderly patients are at risk of deep venous thrombosis of the lower extremities. Moreover, repeated abdominal operations cause substantial trauma to the abdominal wall and have a high risk of wound infection and severe intraperitoneal adhesions. The robotic surgical system overcomes the limitations of laparoscopy in terms of the visual field and the flexibility and stability of the instruments [21], making it possible for surgeons to perform high-quality minimally invasive surgery, especially in narrow, deep and confined areas such as the hepatic hilum or the transection plane of the liver [13, 22, 23].

Lee et al. [24] reported 15 cases of hepatolithiasis treated by using robotic surgical systems. Compared with the laparotomy group, the RLS group experienced less bleeding and shorter hospitalization times; there were no significant differences in the incidence of complications, the rate of residual stones, the rate of stone recurrence or the rate cholangitis recurrence between the two groups. Chen et al. [25]. performed a robotic left hepatectomy combined with biliary-enteric anastomosis in a patient with complex hepatolithiasis. The operation duration was 390 min, and blood loss was 300 ml. The patient was discharged 9 days after the operation, and no recurrence was observed over the 20 months of follow-up. Kim et al. [26] performed RLS on four patients with intrahepatic bile duct stones; the mean operation time was 455.8 min, the mean blood loss was 250 ml, and the mean duration of postoperative hospital stay was 7 days. Compared with the patients of the aforementioned studies, the patients in our RLS group tended to have longer postoperative hospital stays. The reasons may include complicated operations, hilar translocation due to recurrent bile duct inflammation, severe perihepatic adhesions caused by multiple previous operations, and the relatively high rate of complications in our patients.

The preliminary results showed that although the operation time was longer in the RLS group than in the OS group, RLS had obvious advantages in terms of blood loss, blood transfusion, postoperative recovery, and postoperative hospital stay. The incidence of complications and the stone clearance rate were not significantly different between the two groups. These results showed that the robotic surgical system is safe and effective for the treatment of complicated hepatolithiasis, providing minimally invasive surgical treatment for the disease.

However, the cost of RLS is higher than that of OS. The difference in cost between the two groups was due to the start-up costs of the robotic surgical system and the cost of disposable high-value supplies, such as Maryland bipolar forceps, Harmonic curved shears, large needle driver, and fenestrated bipolar forceps, which cost approximately $5000 in total. The start-up costs of the robotic system and high-value consumables are not covered by medical insurance. This portion of the cost must be paid by the patients if they choose to undergo robotic surgery. These factors limit the widespread application of the robotic surgical system in our department. Because of the high purchase and maintenance costs of the robot operating system, the average hospitalization cost for the RLS group was higher than that for the OS group. The faster recovery and shorter hospitalization in the RLS group than in the OS group reduced part of the postoperative cost. However, these reductions were not enough to offset all of the start-up costs and disposable high-value consumables. As a result, this study included only 26 cases of RLS. To reduce the bias caused by differences in age, sex, history of previous surgery, and distribution of stones, the PSM method was used to match RLS and OS patients at a ratio of 1:2.

Adhesiolysis, dissection of the hepatic hilum and treatment of bile duct stenosis are key points in the treatment of complex hepatolithiasis. For complex hepatolithiasis with hepatic hilar translocation and adhesion formation, separation of the hilar adhesions and exposure of the hilar bile ducts are time consuming, difficult, and risky. These procedures are also challenging to perform in OS. When the robotic surgical system was used for surgery of the hepatic hilum, we first gradually separated the tissue adhering to the capsule of the liver along the surface of the liver, moving from shallow to deep and from right to left. A combined sharp and blunt dissection method was applied to find a gap in the tissue, and then, the intraabdominal organs were separated from the liver surface. The sites of dense adhesions were mostly around drainage tubes, chronic fistulas, or abscesses. When separating adhesions, it is advisable to cut tough scars with electrocoagulation hooks or scissors. The hepatic hilum often translocates into the liver parenchyma and is encapsulated by dense fibrous scar tissue. At this point, the liver capsule can be incised at the adhesion site between the lower edge of segment IV and the hepatoduodenal ligament. The hepatic plate is then lowered, and the common hepatic duct is exposed. If necessary, the liver parenchyma can be split along the middle fistula of the liver, exposing the hepatic hilum from top to bottom. Part of the liver parenchyma in segments IVb and V may be resected. According to our past experience with OS, the use of RLS for the treatment of complex hepatolithiasis is completely in line with the principles of treatment for hepatolithiasis. The prolonged operation time may be related to the docking of the robot and the learning curve associated with the robotic system, but the prolonged operation time did not result in increased complications. In addition, as the surgical technique is improved, the operation time may be shortened. The use of 3D magnified vision, intraoperative ultrasound, and choledochoscopy exploration can compensate for the lack of tactile feedback in the robotic surgical system.

In conclusion, the short-term and long-term results of this study indicate that the use of the robotic surgical system for the treatment of complicated hepatolithiasis is safe, effective, and feasible compared with OS. There was no difference in the stone clearance or calculi recurrence rates between the two groups. RLS is accompanied by less intraoperative blood loss, a lower transfusion rate, a shorter postoperative hospitalization time, and a faster postoperative recovery than OS. Thus, RLS is a suitable, minimally invasive procedure for the treatment of complicated hepatolithiasis. This study had a limited sample size and did not address all types of complex hepatolithiasis. This was also a retrospective study with a short follow-up period. The results of this study need to be further confirmed by large-scale multicenter prospective randomized controlled trials and long-term follow-up.

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Compliance with ethical standards

Disclosure Jie Shu, Xiao-jun Wang, Jian-wei Li, Ping Bie, Jian Chen, Shu-guo Zheng have no conflicts of interest or financial ties to disclosure.

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