Original Article

Robotic major liver resections: Surgical outcomes compared with open major liver resections

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Backgrounds/Aims: Laparoscopic major liver resections are still considered innovative procedures despite the recent development of laparoscopic liver surgery. Robotic surgery has been introduced as an innovative system for laparoscopic surgery. In this study, we investigated surgical outcomes after major liver resections using robotic systems. **Methods:** From January 2009 to October 2018, 70 patients underwent robotic major liver resections, which included conventional major liver resections and right sectionectomy. The short-term and long-term outcomes were compared with 252 open major resections performed during the same period. **Results:** Operative time was longer in the robotic group (472 min vs. 349 min, $p < 0.001$). However, estimated blood loss was lower in the robotic group compared with the open resection group (269 ml vs. 548 ml, $p=0.009$). The overall postoperative complication rate of the robotic group was lower than that of the open resection group (31.4% vs. 58.3%, $p < 0.001$), but the major complication rate was similar between the two groups. Hospital stay was shorter in the robotic group (9.5 days vs. 15.1 days, $p=0.006$). Among patients with HCC, cholangiocarcinoma, and colorectal liver metastasis, there was no difference in overall and disease-free survival between the two groups. After propensity score matching in 37 patients with HCC for each group, the robotic group still showed a shorter hospital stay and comparable long-term outcomes. **Conclusions:** Robotic major liver resections provided improved perioperative outcomes and comparable long-term oncologic outcome compared with open resections. Therefore, robotic surgery should be considered one of the options for minimally invasive major liver resections. **(Ann Hepatobiliary Pancreat Surg 2021;25:8-17)**

Key Words: Robotic hepatectomy; Open hepatectomy; Major liver resection; Surgical outcomes

INTRODUCTION

Accumulating evidence has shown that laparoscopic liver resection is a safe and effective treatment for benign and malignant liver disease.[1-3] In two international consensus conferences on laparoscopic liver resection, minor liver resection has been recommended as a standard approach.[4] The size and location of the tumors are no longer limiting factors for the laparoscopic approach. Despite the recent dramatic advances in laparoscopic liver resection, laparoscopic major liver resection is still considered an innovative procedure.[4] This consideration is mainly based on the incompletely defined risks of laparoscopic major liver resection, which are related to not only operative complexity and high potential for major bleeding with major liver resection, but also the limitations of laparoscopic technology.

Robotic systems overcome the inherent disadvantages of laparoscopic technology and facilitate highly complex laparoscopic procedures such as fine dissection around vascular structures and ease of suturing and knot tying even in a deep and narrow space.[5] Robotic systems eliminated one potential obstacle for adoption of the minimally invasive approach among surgical fields and several studies have demonstrated the feasibility and safety of robotic liver resection.[5-7] Given that liver resection consists of several operative procedures and wide ranges of operative complexity, the advantages of robotic liver resection might be more prominent in more complex major liver resections.[8,9] Although a few studies addressed the short-term outcomes of robotic major liver resection (RMLR),[10] studies on long-term outcomes are still lacking. In this

study, we investigated and compared short- and long-term outcomes of RMLR with open major liver resection.

MATERIALS AND METHODS

Patient cohort and study design

From January 2009 to October 2018, 70 patients underwent major liver resections due to benign and malignant liver diseases with the da Vinci Surgical system (Intuitive Surgical, Sunnyvale, CA, USA) in the Yonsei University College of Medicine, Seoul, Korea. During the same period, 252 patients underwent open major liver resections. Major liver resections were defined as the resections of three or more Couinaud segments. In addition, the right-side sectionectomy including right posterior sectionectomy, right anterior sectionectomy and extended right posterior sectionectomy were included in major liver resections due to technical challenges in a laparoscopic field.[11,12] Initially, robotic major liver resection was recommended for a patient with single tumor less than 5 cm in diameter, adequate remnant liver volume, Child A with no significant portal hypertension, no anatomical variations and a good healthy condition. With increases of experience, the indication has been extended to a patient with larger tumor, multiple tumors and anatomical variations. The indication for major liver resections were the same in the open and robotic groups as follows: no clinically significant portal hypertension and enough residual liver volume according to the background liver condition.[13]

Perioperative and postoperative short-term outcomes were compared between the robotic and open major liver resection groups. The post-operative complications were evaluated using the modified Clavien System in both groups.[14] Long-term oncologic outcomes were compared between patients in the two groups who had malignant liver diseases. Patients who received robotic surgery were informed of the innovative nature of the robotic system before surgery. Written informed consents were obtained before surgery from all patients. This study was approved by the Institutional Review Board of Severance Hospital (IRB No. 4-2020-0460), which waived the requirement for informed consent due to the retrospective nature of this study. This study was performed in accordance with the ethical guidelines of the Would Medical Association Declaration of Helsinki 2013.

Operative procedures

Robotic hepatectomy

The operative procedures were described in detail in our previous studies.[6,15,16] Briefly, patients were positioned supine with 15° reverse Trendelenburg position. We used five ports for all procedures: a 12 mm camera port, a 12 mm assistant port, and three 8 mm robotic arm ports. Liver mobilization and hilar dissection were performed with same method as open surgery. Individual ligation of inflow was a preferred approach for hemi-hepatectomy and the glissonian pedicle approach was used for central and right-side sectionectomy. Since 2016, the ischemic demarcation line has been checked by an Indocyanine green (ICG) fluorescence image with a robotic firefly system.[15] Initially, 2 mg ICG was directly injected into the selected portal vein. Now, 5 mg ICG was injected into the peripheral vein after the occlusion of inflow of the target liver.[17] Parenchymal transection was conducted using harmonic curved shears and Maryland bipolar forceps. For secure exposure of the parenchymal transection plane, we used the rubber band technique.[6] Major hepatic vein branches were fully exposed and then ligated using robotic Hem-o-rock clips. Each hepatic vein was divided using a linear vascular stapler. Pfannenstiel incision or previous operation incision line were used to retrieve a specimen.

Open hepatectomy

Open hepatectomies were done with a right subcostal and upper midline incision. Liver was mobilized by section of round, falciform ligaments and ipsilateral coronary and triangular ligaments. Intraoperative ultrasound was used before starting liver hilum dissection. Hepatic artery and portal vein of resection position were individually ligated. Each bile duct was divided after total exposure of the hilar plate. Parenchymal transection was done following the ischemic demarcation line using an ultrasonic dissector (CUSA Excel, Integra). Pringle maneuver and hanging maneuver were selectively used depending on the case.

Statistical analysis

All continuous data were presented as the mean (standard deviation) and compared using a Student's t-test. Categorical variables were compared using the Chi-square test or Fisher's exact test as appropriate.

Statistical analyses were carried out using SPSS 23 for Windows (SPSS Inc., Chicago, IL, USA). In patients with liver malignancy, disease-free and overall survival rates were calculated using the Kaplan−Meier method and the difference was measured by log-rank test.

In patients with hepatocellular carcinoma (HCC), propensity score matching analysis was performed to evaluate short- and long-term outcomes between the robotic and open major liver resection groups. Categorical variables were analyzed with the chi-square test or the Fisher's exact test. Continuous variables were analyzed with the Mann-Whitney U test before matching HCC patients. The two groups were matched using a propensity score in 1:2 ratio, based on age, chronic liver dx, op name, tumor size, microvascular invasion and tumor markers (AFP, PIVKA-II). Matched continuous data were compared using the paired t-test, the Mann-Whitney U test, as appropriate, and categorical variables were compared using a McNemar's test. PSM statistical analyses were carried out using SAS (version 9.4, SAS Inc., Cary, NC, USA), R

package, version 3.4.3 (http://www.R-project.org). The paired result was significant and reliable because some variables with huge gap (AFP, PIVKA) were adjusted with no significant difference.

RESULTS

A total of 322 patients underwent robotic or open major hepatectomies: 70 patients received robotic major liver resections, which included conventional major liver resections and sectionectomies of the liver, and 252 patients received open major liver resections during the same period. Patient demographics, tumor characteristics and operative procedures are listed in Table 1. Hepatocellular carcinoma was the most common diagnosis in both robotic (n=40) and open (n=170) groups.

Resection type

Operation type is summarized in Table 1. Robotic major liver resections included right hepatectomy (n=16), left

Table 1. Patient demographics, tumor characteristics, and operative procedures in patients with robotic resection and open major liver resection

Variables (mean±SD)	Robotic resection (N=70)	Open resection (N=252)	p
Age (years)	54.1±11.5	59.3±10.1	0.71
Sex			0.001
Male	44 (62.8%)	189 (75.0%)	
Female	26 (37.2%)	63 (25.0%)	
BMI (kg/m^2)	24.1±3.2	23.7±3.6	0.56
Underlying liver disease			0.51
None	32 (45.7%)	104 (41.2%)	
Hepatitis B	37 (52.8%)	138 (54.8%)	
Hepatitis C	1 (1.5%)	10 (4.0%)	
Diagnosis			
Hepatocellular carcinoma	40 (57.1%)	170 (67.5%)	
Liver metastasis	8 (11.4%)	33 (13.1%)	
Intrahepatic duct stone	9 (12.9%)	2 (0.8%)	
Cholangiocarcinoma	6 (8.6%)	47 (18.7%)	
Complicated liver cyst	6 (8.6%)	0 (0%)	
Stricture of intrahepatic duct and cholangitis	1 (1.4%)	0 (0%)	
Operation type			
Right hemihepatectomy	16 (22.8%)	120 (47.6%)	
Left hemihepatectomy	38 (54.3%)	56 (22.2%)	
Central bisectionectomy	2 (2.9%)	26 (10.3%)	
Right posterior sectionectomy	6 (8.5%)	32 (12.8%)	
Extended right posterior sectionectomy	5 (7.2%)	5 (1.9%)	
Right anterior sectionectomy	3 (4.3%)	13 (5.2%)	

Data are shown as mean with standard deviation
BMI, body mass index

hepatectomy (n=38), central bisectionectomy (n=2), right posterior sectionectomy (n=6), extended right posterior sectionectomy (n=5) and right anterior sectionectomy (n=3). Left hepatectomy was most frequently performed among all operation types in the robotic group (n=38, 54.3%), while right hepatectomy was most frequent in the open group (n=120, 47.6%).

Perioperative outcomes and postoperative complications between the two groups

Postoperative outcomes are described in Table 2. The operative time was significantly longer in the robotic group (472 min vs. 349 min, $p < 0.001$); however, the estimated blood loss was significantly lower in the robotic group compared with the open group (269 ml vs. 548 ml,

$p=0.009$). Postoperative complication rate of the robotic group was lower than the open resection group ($p < 0.001$) and hospital stay was significantly shorter in the robotic group (9.5 days vs. 15.1 days, $p=0.006$). Among 12 cases of bile leakage, only one case occurred in the robotic group. No post-operative bleeding was observed in both groups. Furthermore, all patients with liver malignancy in the robotic group achieved R0 resection (range of resection margin, 0.1-11.7 cm). Perioperative outcomes were also compared after dividing the robotic group into initial 35 and recent 35 cases with the open groups (Table 3). The gap in operative time between the robotic and open groups decreased in the recent cases. The recent robotic cases still provided a low complication rate and shorter hospital stay compared with those of the open group. Seven open con-

Table 2. Comparison of perioperative outcomes between the two groups

Variables (mean±SD)	Robotic resection (N=70)	Open resection (N=252)	p
Operative time (min)	472.0±202.7	349.0±144.7	<0.001
Estimated blood loss (ml)	269.9±353.8	548.5±536.7	0.009
Postoperative complication	22 (31.4%)	147 (58.3%)	<0.001
I	3 (4.2%)	71 (28.2%)	
II	17 (24.3%)	55 (21.8%)	
III, IV	2 (2.9%)	20 (7.9%)	
V (death)	0 (0%)	1 (0.4%)	
Major complication rate (grade III or more)	2 (2.9%)	21 (8.3%)	0.11
Bile leakage	1 (1.42%)	12 (4.7%)	0.21
Post-operative bleeding	0 (0%)	0 (0%)	-
Length of hospital stay (days)	9.5±6.3	15.1±8.2	0.006

Data are shown as the mean with the standard deviation
Complication was graded according to Clavien-Dindo classification

Table 3. Comparison of perioperative outcomes of initial and recent robotic cases with open groups

Variables (Mean±SD)	Initial robotic major (N=35)	Open major (N=66)	p	Recent robotic major (N=35)	Open major (N=186)	p
Operative time (min)	529.2±194.0	300.7±118.2	<0.001	425.2±201.7	340.9±137.3	0.033
Estimated blood loss (ml)	316.6±327.3	579.8±548.2	0.003	246.1±393.6	469.6±495.0	0.63
Postoperative complication	11 (31.4%)	40 (60.6%)	0.013	11 (31.4%)	107 (57.5%)	0.016
Major complication rate	1 (2.9%)	8 (28.9%)	0.15	1 (2.9%)	13 (6.9%)	0.70
Bile leakage	1 (2.9%)	3 (4.5%)	0.54	0 (0%)	9 (4.8%)	0.13
Post-operative bleeding	0 (0%)	0 (0%)		0 (0%)	0 (0%)	
Length of hospital stay (days)	11.1±8.3	15.7±9.6	0.030	8.3±3.8	14.0±6.7	<0.001
Open conversion	3 (8%)			4 (11%)		

Data are shown as the mean with the standard deviation and the percentage in brackets
Complication was graded according to Clavien-Dindo classification
Complications with grades III or more were classified as major complication

version cases (10%) were observed in our study (Table 4). Bleeding was the main reason of open conversion (57.1%). Diaphragm abutting finding and difficult cancer lesion for approach were other reasons for open conversion. Only one case had transfusion due to decreased hemoglobin after surgery. No significant further severe complications were reported in all seven converted cases.
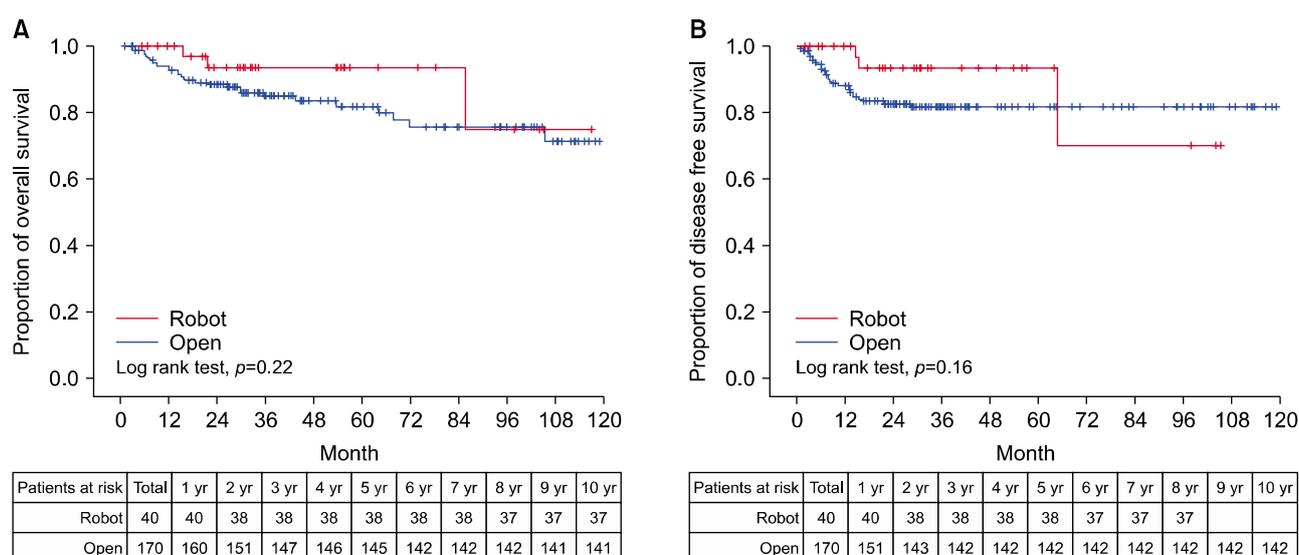
Long−term outcomes in patients with liver malignancy

In patients with HCC, there were no significant differences in overall (p=0.22) and disease-free survival (p=0.16) between the two groups (Fig. 1). In the robotic

and open groups of patients with HCC, the 1-, 3- and 5-year overall survival rates were 100%, 93% and 93% compared with 93%, 85% and 81%, respectively; disease-free survival rates were 100%, 93% and 93% compared with 88%, 82% and 82%. Liver metastasis groups also showed no differences in overall (p=0.73) and disease-free survival (p=0.57) (Fig. 2). Cholangiocellular carcinoma groups had no differences in overall (p=0.38) and disease-free survival (p=0.49) (Fig. 3) In the robotic and open groups of patients with liver metastasis, the 1-, 3- and 5-year overall survival rates were 87%, 87% and 87% compared with 96%, 80% and 80%, respectively, while disease-free survival rates were 85%, 85% and 85% compared with 89%, 74% and none in 5 year. In the ro-

Table 4. The cases of open conversion in the robotic group

|	Diagnosis	Operation type	Reason
1	CCC	Left hemihepatectomy	Bleeding during parenchymal transection
2	IHD stone	Right hemihepatectomy	Difficulty in dissection of the liver hilum due to anatomical alternation
3	HCC	Extended right posterior sectionectomy	Poor exposure due to tumor adhesion to the diaphragm
4	HCC	Extended right posterior sectionectomy	Bleeding during parenchymal transection
5	HCC	Extended right posterior sectionectomy	Bleeding during parenchymal transection
6	HCC	Right posterior sectionectomy	Technical inaccessibility to parenchymal trasenction
7	HCC	Right anterior sectionectomy	Bleeding during parenchymal transection

CCC, cholangiocellular carcinoma; IHD stone, intra-hepatic duct stone; HCC, hepatocellular carcinoma

Patients at risk	Total	1 yr	2 yr	3 yr	4 yr	5 yr	6 yr	7 yr	8 yr	9 yr	10 yr
Robot	40	40	38	38	38	38	38	38	37	37	37
Open	170	160	151	147	146	145	142	142	142	141	141

Patients at risk	Total	1 yr	2 yr	3 yr	4 yr	5 yr	6 yr	7 yr	8 yr	9 yr	10 yr
Robot	40	40	38	38	38	38	37	37	37		
Open	170	151	143	142	142	142	142	142	142	142	142

Fig. 1. Survival analysis between open and robot resection groups regarding hepatocellular carcinoma. (A) Overall survival analysis in patients with hepatocellular carcinoma (p=0.22, the 1-, 3- and 5-year survival rate of robotic case: 100%, 93% and 93%/open case: 93%, 85% and 81%). (B) Disease-free survival analysis in patients with Hepatocellular carcinoma (p=0.16, the 1-, 3- and 5-year survival rate of robotic case: 100%, 93% and 93%/open case: 88%, 82% and 82%).
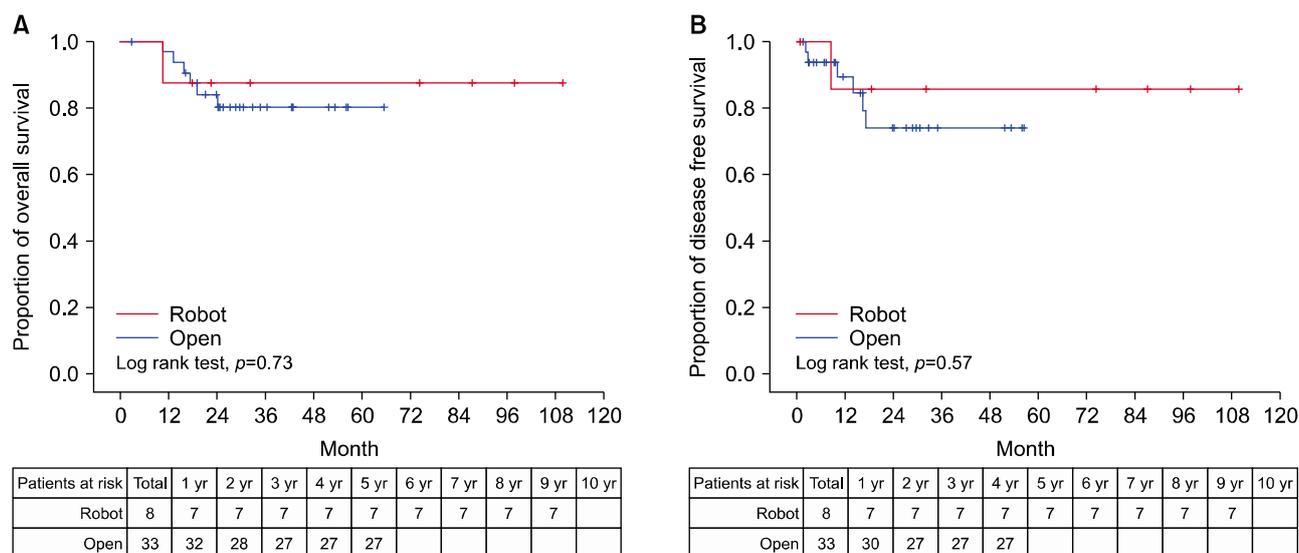
Fig. 2. Survival analysis between open and robot resection group regarding liver metastasis. (A) Overall survival analysis in patients with liver metastasis (p=0.73, the 1-, 3- and 5-year survival rate of robotic case: 87%, 87% and 87%/open case: 96%, 80% and 80%). (B) Disease-free survival analysis in patients with liver metastasis (p=0.57, the 1-, 3- and 5-year survival rate of robotic case: 85%, 85% and 85%/open caser: 89%, 74% and none in 5 year).
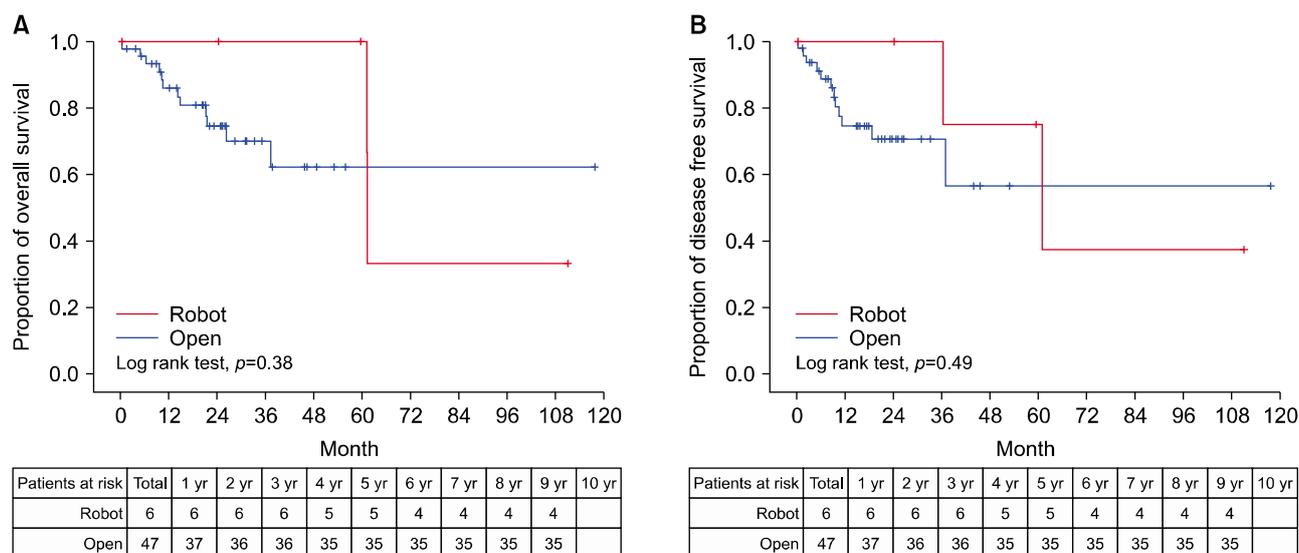
Fig. 3. Survival analysis between open and robot resection groups regarding cholangiocellular carcinoma. (A) Overall survival analysis in patients with Cholangiocellular carcinoma (p=0.38 the 1-, 3- and 5-year survival rate of robotic case: 100%, 100% and 100%/open case: 86%, 70% and 62%). (B) Disease-free survival analysis in patients with Cholangiocellular carcinoma (p=0.49 the 1-, 3- and 5-year survival rate of robotic case: 100%, 100% and 75%/open case: 74%, 70% and 56%).

botic and open groups of patients with cholangiocellular carcinoma the 1-, 3- and 5-year overall survival rates were 100%, 100% and 100% compared with 86%, 70% and 62%, respectively, while disease-free survival rates were 100%, 100% and 75% compared with 74%, 70% and 56%.

Perioperative and long-term outcomes after propensity score matching in patients with HCC

Unmatched and matched HCC patient characteristics are summarized in Table 5. Perioperative outcomes are summarized in Table 6. In the unmatched cohort, the robotic HCC group showed less blood loss and shorter hospital stay than the open HCC group (301 ml vs. 542 ml,

Table 5. Comparison of perioperative outcomes between the two groups in patients with hepatocellular carcinoma before and after propensity score matched analysis

Variables	Before propensity score matching			After propensity score matching		
	Open (n=170)	Robot (n=40)	p	Open (n=37)	Robot (n=37)	p
Age	57.64±10.13	53.08±10.73	0.012	54.70±9.19	54.54±9.65	0.87
Sex			0.96			0.56
Male	128 (75.2%)	30 (75%)		27 (72.9%)	29 (78.3%)	
Female	42 (24.8%)	10 (25%)		10 (27.1%)	8 (21.7%)	
Underlying liver disease			0.52			0.99
None	30 (17.6%)	5 (12.5%)		6 (16.2%)	5 (13.5%)	
Hepatitis B	131 (77.0%)	34 (85%)		30 (81.1%)	31 (83.7%)	
Hepatitis C	9 (5.4%)	1 (2.5%)		1 (2.7%)	1 (2.8%)	
Operation types			0.061			0.44
Right hepatectomy	115 (67.6%)	24 (60.0%)		26 (70.2%)	24 (64.8%)	
Left hepatectomy	33 (19.4%)	14 (35%)		6 (16.2%)	11 (29.7%)	
Central bisectionectomy	22 (13.0%)	2 (5%)		5 (13.6%)	2 (5.5%)	
Tumor size (cm)	4.36±3.09	3.44±3.74	0.10	3.71±2.76	3.54±3.87	0.75
Tumor counts			0.006			NA
One	170 (100%)	37 (92.5%)		37 (100%)	34 (91.9%)	
Multiple	0 (0%)	3 (7.5%)		0 (0%)	3 (8.1%)	
MVI	84 (49.4%)	15 (37.5%)	0.17	13 (35.1%)	13 (35.1%)	0.10
AFP	3192.53 (0-224633.90)	109.58 (1.37-2216.90)	0.38	159.35 (0-3556.57)	94.59 (1.37-2216.9)	0.42
PIVKA II	1981.49 (0.91-75000)	252.72 (11-1318)	0.66	197.95 (13-2000)	266.14 (11-1318)	0.42

Data are shown as the mean with the standard deviation
MVI, microvascular invasion; AFP, alpha-fetoprotein tumor marker; PIVKA II, protein induced by vitamin K absence or antagonist II

Table 6. Perioperative outcomes in Hepatocellular carcinoma after propensity score matching
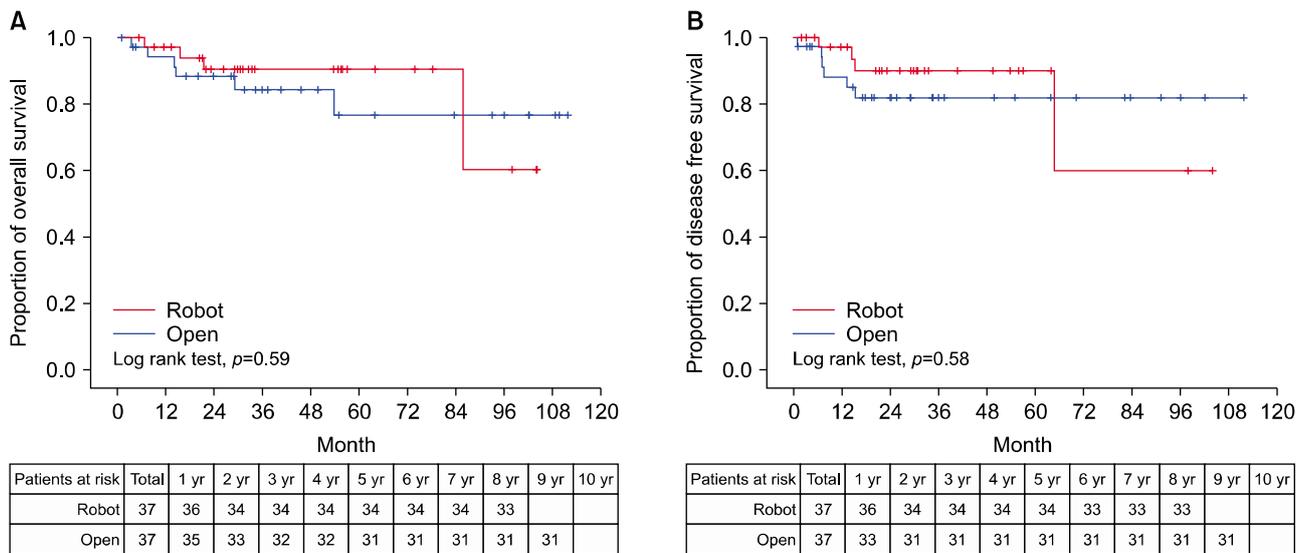
Variables	Before propensity score matching			After propensity score matching		
	Open (n=170)	Robot (n=40)	p	Open (n=37)	Robot (n=37)	p
Operative time (min)	305.93±105.11	484.58±224.96	<0.001	312.22±90.048	496.81±227.58	<0.001
Estimated blood loss (ml)	542.88±578.30	301.50±375.64	0.012	508.38±625.69	321.89±383.44	0.087
Transfusion	27 (15.88%)	3 (7.5%)	0.18	7 (18.92%)	3 (8.11%)	0.17
Complication			0.18			0.070
I, II	83 (48.82%)	14 (35%)		21 (56.76%)	13 (35.14%)	
III, IV	13 (7.65%)	1 (2.5%)		1 (2.70%)	1 (2.70%)	
R1 resection	40 (100%)	0 (0%)	NA	2 (5.41%)	0 (0%)	NA
Length of hospital stay (days)	13.8±7.1	9.2±6.7	<0.001	13±6.4	9.4±6.9	0.033

Data are shown as the mean with the standard deviation
R1 resection, removal of all macroscopic disease with microscopic positive margins

p=0.01, 9 days vs. 13 days, p<0.01). Operative time was longer in the robotic group (484 min vs. 305 min, p<0.001). All 40 robotic patients achieved R0 resection. In contrast, 3 open patients were reported with remnant cancer. In the matched 37 patient subgroup analysis, oper-

ative time was still longer in the robotic group (496 min vs. 312 min, p<0.001). In addition, hospital stay was shorter in the robotic group (9 days vs. 13 days, p=0.003). Overall survival and disease-free survival showed no critical difference between the two groups (p=0.59, p=0.58)

A

B

Patients at risk	Total	1 yr	2 yr	3 yr	4 yr	5 yr	6 yr	7 yr	8 yr	9 yr	10 yr
Robot	37	36	34	34	34	34	34	34	33		
Open	37	35	33	32	32	31	31	31	31	31	

Patients at risk	Total	1 yr	2 yr	3 yr	4 yr	5 yr	6 yr	7 yr	8 yr	9 yr	10 yr
Robot	37	36	34	34	34	34	33	33	33		
Open	37	33	31	31	31	31	31	31	31	31	

Fig. 4. Survival analysis between open and robot resection groups regarding hepatocellular carcinoma after propensity score matching. (A) Overall survival analysis in patients with hepatocellular carcinoma after PSM (p=0.59, the 1-, 3- and 5-year survival rate of robotic case: 97%, 90% and 90%/open case: 94%, 84% and 76%). (B) Disease-free survival analysis in patients with Hepatocellular carcinoma after PSM (p=0.58, the 1-, 3- and 5-year survival rate of robotic case: 97%, 90% and 90%/open case: 88%, 82% and 82%).

(Fig. 4). Overall survival rates of the robotic and open groups at 1, 3 and 5 years were 97%, 90% and 90% compared with 94%, 84% and 76%, respectively, while disease-free survival of the groups at 1, 3, and 5 years were 97%, 90% and 90% compared with 88%, 82% and 82%.

DISCUSSION

Even though laparoscopic liver resection has evolved dramatically, laparoscopic major liver resection is still performed at an expert center and is considered an innovative procedure,[18,19] which may be attributed to the anatomical complexity of the liver, high potential of major bleeding, and the inherent limitations of laparoscopic technology. Robotic systems eliminated fulcrum effect and provided instruments with seven degrees of freedom. These technical advances allow surgeons to use the same dissecting technique as in open surgery. An analysis of the ACS-NSQIP data showed that major liver resection was one of the risk factors for open conversion during minimally invasive procedures, and robotic systems were associated with a lower conversion rate than laparoscopic liver resection.[20] Recently, Chong et al.[21] reported that robotic systems allowed major hepatectomy or highly scored hepatectomy to be performed with a minimally invasive

approach. In our series, the procedures of all kinds of major liver resections, including mobilization of the right and left liver, individual ligation of the liver hilum, the extra-hepatic glissionean approach and parenchymal transection following the ischemic demarcation line, were all safely reproduced in the laparoscopic field using the robotic system. The open conversion rate in our study was 10%, which is lower than that of laparoscopic major hepatectomy reported in previous studies (14%-25.8%).[2-4,22]

In addition to the reproduction of open procedures, laparoscopic surgery must be able to achieve at minimum the same quality of surgical outcomes as open surgery. With the advantages of mini-incision, laparoscopic liver resection showed a lower complication rate and shorter hospital stay compared with open liver resection in previous meta-analyses.[23-25] Similar to the advantages of laparoscopic liver resection, the robotic major liver resection group showed a reduced minor complication rate and shorter hospital stay compared with open major hepatectomy in our studies. Longer operative time was found in the robotic group compared with the open group. However, the operative time for left hepatectomy has gradually decreased compared to our previous study[15] and the gap of operative time between the robotic and open group decreased in the set of recent cases.

Parenchymal transection is one of the challenging procedures for major liver resection, which is more problematic in robotic surgery because of the limited available instruments for parenchymal transection.[4] The main challenge during parenchymal transection is severe bleeding, which usually originates from inadvertent injury to major hepatic vein branches. In our series, the second case of robotic left hepatectomy had to be converted to open laparotomy due to uncontrolled bleeding from the middle hepatic vein branch during parenchymal transection. After this experience, we modified the traction method during parenchymal transection, named the "rubber band traction" method.[6,15,26] This method involves simultaneous use of all three robotic arms during parenchymal transection. Therefore, bleeding can be effectively controlled by compression using the third robotic arm or by compression followed by suture ligation. In addition, ICG fluorescence imaging has been used to identify an ischemic demarcation line through an direct or indirect staining technique, which can facilitate transecting an exact anatomical plane during parenchymal transection.[15] In our series, the estimated blood loss in the robotic group was 270 ml, which was significantly lower than that of the open group (550 ml, p-value=0.009). Since the introduction of the rubber band traction method, open conversion has been required in just three patients (4.4%) due to uncontrolled bleeding during parenchymal transection in this study. However, most of these open conversion cases occurred in extended right posterior sectionectomy, which requires the dissection and ligation of the medium-sized portal pedicles from the right anterior portal pedicles during the later stage of parenchymal transection. Because the parenchymal transection plane is usually formed in the deep area during the later stage of extended right posterior sectionectomy, it is sometimes difficult to finely and safely dissect the portal pedicles and hepatic vein branches. Three patients (60%) of five patients who underwent extended right posterior sectionectomy experienced open conversion in our series. Therefore, robotic surgery with current instruments seems safe and effective for anatomical parenchymal transection, but might not be suitable for wide non-anatomical parenchymal transection such as extended right posterior sectionectomy.

The oncologic outcomes after robotic liver resection in patients with liver malignancies are an important issue.

Most previous studies focused on curative resection rate, which ranges from 81% to 100%.[9,27-29] Only two studies dealt with long-term outcomes after robotic liver resection in patients with HCC.[30,31] Chen et al.[31] reported than robotic liver resection showed a comparable 3-year disease-free survival rate compared with open liver resection in patients with HCC. Compared with laparoscopic liver resection, robotic liver resection provided similar long-term outcomes in a study in Hong Kong.[30] In agreement of the previous studies, disease-free and overall survival rates in patients with HCC were similar to those of robotic and open major liver resection before and after propensity-score matching analysis in this study. In our data, all patients with liver metastasis and intrahepatic CCC in the robotic group received R0 resection and showed comparable long-term outcomes compared with open liver resections. However, the number of patients with liver metastasis and intrahepatic CCC was small and their long-term outcomes should be further investigated in a large-scaled study.

CONCLUSION

Robotic major liver resections showed improved perioperative outcomes and comparable long-term oncologic outcome compared with open resections. After propensity score matching in HCC patients, the robotic resection group still showed shorter hospital stay and comparable long-term outcome compared with the open group. Therefore, robotic surgery should be considered one of the options for minimally invasive major liver resections.

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AUTHOR CONTRIBUTIONS

Conceptualization: GHC. Data curation: HYY, SYR, DHH, JSC, GHC. Formal analysis: HYY, SYR. Funding Acquisition: HYY. Investigation: DHH, JSC. Methodology:

HYY, GHC. Project administration: GHC. Resources: HYY, GHC. Software: HYY, SYR. Supervision: GHC, SYR. Validation: HYY, GHC. Visualization: HYY, SYR, GHC. Writing - Original draft: HYY. Writing - Review and editing: HYY, SYR, GHC.

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