Review Article

A narrative review of the current and future role of robotic surgery in liver surgery and transplantation

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Background: Minimally invasive surgery (MIS) is the technique of choice in selected patients for the treatment of liver tumors. The robotic approach is considered today the natural evolution of MIS. The application of the robotic technique in liver transplantation (LT) has been recently evaluated, especially in the living donation. The aim of this paper is to review the current role of the MIS and robotic donor hepatectomy in the literature and to evaluate the possible future implication in the transplant field.

Methods: We conducted a narrative review using PubMed and Google Scholar for reports published so far, using the following keywords: minimally invasive liver surgery, laparoscopic liver surgery, robotic liver surgery, robotic living donation, laparoscopic donor hepatectomy and robotic donor hepatectomy.

Results: Several advantages have been claimed in favor of robotic surgery: three-dimensional (3-D) imaging with stable and high-definition view; a more rapid learning curve than the laparoscopic one; the lack of hand tremors and the freedom of movements. Compared to open surgery, the benefits showed in the studies evaluating the robotic approach in the living donation are: less postoperative pain, the shorter period before returning to normal activity despite sustaining longer operation time. Furthermore, the 3-D and magnification view makes the technique excellent in distinguishing the right plane of transection, vascular and biliary anatomy, associated with high precision of the movements and a better bleeding control (essential for donor safety) and lower rate of vascular injury.

Conclusions: The current literature does not fully support the superiority of the robotic approach versus laparoscopic or open method in living donor hepatectomy. Robotic donor hepatectomy performed by teams with high expertise and in properly selected living donors is safe and feasible. However, further data are necessary to evaluate properly the role of robotic surgery in the field of living donation.

Keywords: Minimally invasive liver surgery; robotic living donation; laparoscopic donor hepatectomy; robotic donor hepatectomy

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Introduction

Minimally invasive surgery (MIS) has become the preferred technique for appropriate patients in the majority of hepatobiliary centers in recent years. The laparoscopic technique was developed in the 1990s. In 1991, Reich *et al.* reported the first laparoscopic non-anatomic hepatectomy (1).

More than 9,000 liver resections utilizing MIS have been reported (2). When compared to open surgery, MIS showed shorter hospital stay and potential earlier access to chemotherapy, lower blood loss and need of transfusion, and better pain control. These results were obtained without affecting the safety of tumor margin (R0 rate), and respecting the parenchymal sparing concept, with similar local recurrence rate and 5-year overall survival (OS). The aim of this paper is to review the current role of the MIS and robotic technique in the transplant field. We conducted a narrative review in accordance with the Narrative Review reporting checklist (available at https://hbsn.amegroups.com/article/view/10.21037/hbsn-21-115/rc) using PubMed and Google Scholar for reports published so far, in English, using the following keywords: minimally invasive liver surgery, laparoscopic liver surgery, robotic liver surgery, robotic living donation, laparoscopic donor hepatectomy, robotic donor hepatectomy.

State of the art in minimally invasive liver surgery

The current role of laparoscopy in liver surgery

MIS found important application in diseases with high pre- and post-operative morbidity and mortality. For example, the use of MIS is extremely beneficial in the treatment of Hepatocellular Carcinoma (HCC) in patients with liver dysfunction. HCC usually needs multiple percutaneous or laparoscopic treatments (wedge resection, microwave or radio frequency ablation), with the intent to bridge or downstage the disease towards liver transplant (LT). MIS better preserves the collateral venous drainage of the abdominal wall, reducing the risk of post-operative ascites, liver insufficiency, and patient decompensation, and reducing intraabdominal adhesions which can complicate the hepatectomy phase during LT (3-10).

Since 2017, in the Eastern hemisphere, 4,095 patients underwent laparoscopic liver resection with a reported mortality rate at 90 days of 0.67% (11).

The application of MIS in liver surgery is also associated with lower blood loss rate, post-operative pain, length of stay, morbidity and better cost-effectiveness compared to open liver surgery (5,12,13). As we pointed out, these results are obtained without affecting the R0 resection rate and the 5-year OS (5,7,8,14-18).

However, despite the increasing application and popularity of the technique, in recent International Consensus Meetings, laparoscopic major hepatic resection was still identified as a pilot procedure, requiring the appropriate expertise of surgeons and facilities, and needing an appropriate learning curve (19).

The application of MIS in liver surgery is restricted by the following main reasons: compared to other organs (gallbladder, colon, adrenal glands) the liver has complex anatomy and requires an accurate plan to control bleeding. Furthermore, its mobilization due to the dimension and the surrounding ligaments is not always easy.

These laparoscopic limitations allow easy performance of minor liver resections (wedge resection or left lobectomy), while major or extended hepatectomies, with or without complex biliary reconstruction, are more challenging and need great surgical expertise and long learning curve. Nowadays, the standard of care for minor hepatectomies (<3 segments)—especially in the anterior segments or left lateral hepatectomy)—is MIS, while larger liver resections are still considered innovative (19).

Nguyen *et al.* showed in their review that only 17% of laparoscopic liver resection were major hepatectomies (7,20-22).

From laparoscopic to robotic liver surgery: a further implementation of MIS

The development of the robotic technique is considered today as the natural evolution of MIS.

In 2002 and 2010, Giulianotti *et al.* described one of the first cases of robotic surgery applied to general surgery (23) and radical major liver resection for hilar cholangiocarcinoma (24). Despite the concern related to high cost, the absence of tactile response and the possible issue of delayed conversion in case of major bleeding, several advantages have been claimed in favor of robotic surgery. The most important advantages are a three-dimensional (3-D) imaging with stable and high-definition view; a more rapid learning curve than the laparoscopic one, thanks to the double console; the lack of hand tremors and the freedom of movements, thanks to the EndoWrist instrumentation.

The last feature is extremely important in liver surgery. The degree of motion of the robotic arms grants a meticulous hepatic hilar and vascular dissection allowing surgeons to suture with greater ease a bleeding parenchyma thanks to the precise handling of the needles (25).

In recent literature, numerous series were devoted to the evaluation of robotic techniques in liver surgery and comparison with open and laparoscopic methods.

Tsung *et al.* performed a 1:1 matched comparison between robotic and open liver surgery. The robotic group showed a lower blood loss and hospital stay compared to open surgery, with similar morbidity and mortality (26).

Marino *et al.* compared 20 and 14 patients who respectively underwent right hepatectomy with laparoscopic or robotic approach (27). Benign and malignant tumors were treated, in particular colorectal metastases and HCC with preserved liver function (Child-Pugh A). To note, the involvement of major hepatic vessels (portal vein branches, inferior vena cava, and major hepatic vein), or the diaphragm were considered contraindications to MIS. Tumor dimension (median lesion size was 45.07 and 44.8±8.1 mm in robotic and laparoscopic arms, respectively), length of surgery, conversion rate (14% and 25% in robotic and laparoscopic arms, respectively), R0 resection rate and post-operative morbidity and mortality were comparable among the robotic and laparoscopic groups.

In 2014, Tsung *et al.* reported the first large matched comparison between 57 robotic (21 major liver resections) and 114 laparoscopic hepatectomies, showing that MIS is a safe and feasible procedure in its operative and postoperative outcomes, and there is no difference in the achievement of R0 margin status between the two groups (26).

With practice, the robotic surgery started to be applied not only to minor liver resections, but also to major hepatectomies.

Choi *et al.* reported 69 robotic liver resections, including 54 major hepatectomies with excellent results in terms of safety and feasibility (28).

A recent review analyzed 14 articles and 447 patients who underwent robotic liver surgery, and confirmed the safety of this procedure and its positive oncological outcome, comparable to laparoscopic approach. Importantly, significant results were also obtained with major robotic hepatectomies (27). A lower blood loss in the robotic approach was reported in comparison with laparoscopic technique, and a 0% increase of mortality rate. The review of both procedures described also a common morbidity rate ranging from 0% to 43%, with similar oncological outcomes in terms of R0 margin.

In conclusion, recent data about outcomes for the robotic approach in liver resections are as good as for the laparoscopic technique.

Some studies, despite generally longer operative time, showed even better result than laparoscopic procedure in term of blood loss (173 *vs.* 325 mL for robotic and laparoscopic approach, respectively, P=0.03), conversion rate (5% *vs.* 12.2%) and morbidity rate (8% *vs.* 10%) (29).

It is important to point out that in liver resection field that the robotic approach is still not as widely used as the laparoscopic one, and published data should be interpreted in light of an ongoing learning curve. Recently, Chen *et al.* evaluated the learning curve in 183 robotic hepatectomies, 92 of which were major hepatectomy. The authors identified three learning phases according to the cases performed. The initial learning curve was barely completed after 15 cases; other 25 cases claimed an increased expertise, whereas the mature phase was already reached in 52 cases. The operation time, hospital stay and blood loss were strictly correlated with the learning steps (30).

To date, as previously suggested in our paper, robotic surgery is granting surgeons with important advantages in terms of freedom of movements and rapid learning curve, but the cost-effectiveness of the procedure and the usually longer duration of operation are still a matter of concern and debate. A recent propensity-matched retrospective cohort study evaluated the cost-benefit of robotic compared to laparoscopic hepatectomy, showing higher cost in the robotic group. However, sufficient data are lacking to properly evaluated the cost-effectiveness of the robotic approach, especially in the transplant field (31-34).

The increased times are especially evident in more complex resections like in the case of posterior liver resections (segments 7 and 8) (26).

For these reasons, despite encouraging results, most of the international guidelines still do not consider the robotic approach superior to the laparoscopic one.

For what concerns minor liver resections, the robotic approach seems to offer similar outcome if compared to laparoscopic surgery, resulting in no actual real advantages. In major and complex liver resections, however, preliminary data show better outcomes of robotic approach in terms of blood loss and morbidity. Robotic surgery, moreover, allows precise execution of major liver resections as compared to the laparoscopic approach, which are feasible only by long trained experts (29).

Tsung *et al.* compared a large cohort of robotic and laparoscopic liver resections. The authors sub analyzed the outcome of minor and major hepatectomies, and showed that 81% of robotic resections were completed with a purely minimally invasive approach (without the use of hand-assist ports or hybrid approach), whereas laparoscopic method allowed a percentage of only 7.1%. To note, the outcomes between the robotic and laparoscopic groups were similar (26).

Furthermore, Wu *et al.* compared the pure laparoscopic approach to the robotic one in liver resection. The introduction of the robotic assistance in liver surgery increased the MIS application by more than twofold and the percentage of major liver resections (i.e., more than three segmentectomies) raised from 15% of laparoscopic series to 39% of robotic one (29).

In light of the above, recent studies evaluated the role of robotic surgery in a specific complex procedure: the liver living donation.

Robotic surgery in LT

Laparoscopic donor hepatectomy: state of the art

Living donation in the transplant field is an important alternative to deceased donors, especially in an era of organs shortage.

Laparoscopic-assisted living donor hepatectomy is well described in the literature, and it is considered a safe procedure with low morbidity and mortality (35,36).

The main limitation to a wider use of Living Donor Liver Transplantation (LDLT) is mainly donor risk. Right hepatic lobe is the graft of choice for adult LDLT, while the left lateral segment is mainly used in pediatric LDLT. Right lobe donor hepatectomy (RLDH) and left lateral liver procurement are not without risk, with a mortality rate of 0.4–0.6%, and 0.05–0.1% respectively, and a morbidity rate ranging from 8.3% to 78.3%. Major causes of morbidity are related to adhesions, wound infections, and hernias, potentially reducible with MIS (37-40).

Therefore, any attempt to decrease the donor morbidity is essential. In the light of the good outcomes in the general surgery, MIS has been evaluated with special attention in the field of living donation.

In ‘95, MIS was first applied to the kidney graft procurement with excellent outcomes (41).

Laparoscopic kidney living donation is now the gold standard technique for kidney donors, with low morbidity and shorter hospital stay than open nephrectomy. The benefits of MIS application in kidney procurement are not simply cosmetic, since this procedure is proven to reduce the post-operative comorbidity, supporting the increase of donation rate (42).

The application of MIS in liver donation, however, has required longer than a decade from the introduction of the procedure to be considered as a possible alternative. The innate technical difficulties of these liver resections, and the significant differences in left and right lobe procurement may explain this delay as well as the improvement in the tools to safely perform these surgeries using MIS techniques.

Today, many authors consider laparoscopic living donor left lateral sectionectomy procurement safe and feasible (43-45). Furthermore, the MIS techniques are not associated with an increased risk of donor death (46).

In 2002, Cherqui *et al.* reported the first full laparoscopic liver living donation for a pediatric recipient (43), with left lateral segmentectomy procurement.

On the other side, only small series of totally laparoscopic right donor hepatectomy were reported, mainly in super selected donors with favorable anatomy, rarely in a pure laparoscopic fashion (hand-assisted procedures or hybrid), often with high conversion and complication rates, especially biliary complications (47-52).

In 2006, Koffron *et al.* reported the first case of laparoscopic-assisted RLDH (53) and in 2010, Han *et al.* performed the first pure laparoscopic RLDH, with excellent results (49). The good outcomes were confirmed by other series (47,48,51,54-58). Giulianotti *et al.* in 2012 reported the first robot-assisted RLDH (59-61).

In 2017, 60 cases of patients underwent pure laparoscopic donor hepatectomy as described by Suh *et al.* (56). Fifty-one patients underwent right hepatectomy, 4 right extended hepatectomy and the others left hepatectomy.

The laparoscopic group was compared to 45 open donors right hepatectomy. The length of postoperative hospital stay (8.4 *vs.* 8.2 days), rate of complications (11.9% *vs.* 8.9%) and re-hospitalizations (4.8% *vs.* 4.4%), were comparable and the only differences referred to the longer operative time (330.7 *vs.* 280.0 min; $P<0.001$) and a higher ratio of multiple bile duct openings (53.3% *vs.* 26.2%; $P=0.01$). However, total operation time decreased with the improvement of surgeon experience. Moreover, the real-time ICG near-infrared fluorescence technique proved to help-identify the exact plane of liver transection. When the authors compared the last 10 pure laparoscopic donor right hepatectomy cases with the open group, the duration of hospital stay was significantly shorter. Similar results and conclusion were reported by Samstein *et al.*, that reported 51 pure laparoscopic donor hepatectomy with good peri operative outcomes (57). Recently, an expert consensus guideline on MIS application on liver donors has been published (46).

Hepatectomy for LDLT

The authors underlined the importance of surgeons’ expertise in open donor hepatectomies and laparoscopic liver hepatectomies. Furthermore, the introduction of depth perception thanks to 3-D laparoscopes and the flexible scope allowing the liver manipulation in small spaces, contributed to the proper adoption of laparoscopic technique (56).

The intent of robot application on living donation is to reduce the morbidity and improve the donor’s outcome without increasing the risk of more severe complications such as bleeding, bile duct or vascular injury.

In particular, robotic surgery in LDLT should maintain at least similar donor safety when compared to laparoscopic and open techniques, while granting an improvement in recovery and rehabilitation process (42). In *Tables 1-4* we summarized the current studies on robotic donor hepatectomy.

As previously reported, the use of robotic technique, especially in RLDH, is expected to be more beneficial, thanks to the advantages related to the robotic assistance. However, some concerns have been raised about its applicability in living liver donation. Lacking of liver-specific features for hepatic dissection, vascular control, time of conversion and the need for a short ischemia time are the main points under discussion (66).

Robotic left lateral sectionectomy (RLLS)

In 2017, Liao *et al.* reported the first successful case report of robot assisted living donor left lateral sectionectomy (LLS) for a 7-month-old male patient affected by congenital biliary atresia (67).

In 2020, Troisi *et al.* compared 25 RLLS to laparoscopic LLS for pediatric LDLT. The blood loss, postoperative patient-controlled analgesia and hospital stay was shorter in the robotic group, maintaining similar morbidity and mortality compared to laparoscopic group (62).

Robotic right lobe donor hepatectomy (RRLDH)

In 2016, Chen *et al.* reported first small series of 13 RRLDH, showing that the robotic approach is safe and feasible. Morbidity and mortality were similar to open surgery (64).

Recently, Broering *et al.* compared the RRLDH to the open right lobe donor hepatectomy (ORLDH) through a propensity score-matched (PSM) analysis (65) and proposed a standardization of robotic liver donor techniques (68). Between 2015 and 2019, 35 and 70 patients underwent RRLDH and ORLDH procedures, respectively. The PSM allowed to reduce the inhomogeneity between the two groups and avoided the selection bias of anatomically favorable donor for RRLDH group. With similar post-operative complications according to Clavien-Dindo classification, the RRLDH group compared to ORLDH showed shorter hospital stay, less use of patient-controlled analgesia and significantly decreased intra operative blood loss. The RRLDH group showed longer mean donor operative time, but the operative time significantly decreased case after case, underlying the importance of the learning curve, as reported by other series (62,63). Only Troisi *et al.* reported comparable operative time between the robotic and laparoscopic group when comparing donors who left lateral sectionectomy (62).

To note, the RRLDH showed a significantly longer warm ischemia, leading so far to no clinical repercussions or graft dysfunction, as reported by the published series (62-65).

Similar results were reported in 2020 by Rho *et al.*, that introduced the robotic technique for more complex donor cases. The study reported 52 living RRLDH, compared to 62 open donors right hepatectomy (CODRH) and 118 laparoscopy-assisted donors right hepatectomy (LADRH). The study showed a longer operative time RRLDH compared to CODRH but less blood loss and lower postoperative pain scores. The authors sub analyzed the operative time according to the cases performed, and the total operative time, console time, and mobilization time gradually decreased. Similarly, although in a slower fashion, hilar dissection and parenchymal dissection times tend to decrease with greater experience. The first warm ischemia time (WIT) significantly increased over the cases, but this could be explained also by the fact that the study included progressively donors with more challenging anatomical features, such as portal vein and biliary duct variations, the presence of right inferior hepatic veins and graft weight more than 800 g (63).

The current and future role of robotic donor hepatectomy

Most authors point out some important strengths in support for the robotic approach.

Compared to open surgery, the donor who underwent robotic liver resection, despite sustaining longer operation time had less postoperative patient-controlled analgesia requirements, and shorter period before returning to normal activity. Most of these benefits should be attributed to the minimally invasive abdominal access points and the use of Pfannestiel incision compared the classic midline incision.

The 3-D and magnification view makes the robotic technique excellent in distinguishing the right plane of transection. Furthermore, the robotic surgery allows an accurate vascular and biliary dissection, particularly during the inferior vena cava isolation. The degree of freedom of the robotic arms increases the stitching capacity, especially in the retro hepatic space, allowing better control of sudden bleeding.

Table 1 Recent studies on robotic liver donor hepatectomy: procedures, vascular anatomy and recipient complications

Authors	N.	Period	Procedure	Type of study	Donor vascular anatomy				Recipient complications
					Portal	Arterial	Bile ducts	Veins	
Troisi *et al.* (62)	25	‘18–‘19	LLS	Retrospective	No variation	Double 1 (4%)	Double in 7 (28%)	N.a.	Overall: 18 (72%)
									Infection: 10 (40%) most common
									Biliary leak: 1 (4%)
									Re-LT: 0 (0%)
									Perioperative death: 1 (4%)
Rho *et al.* (63)	52	‘16–‘19	RH	Retrospective	No variation 46 (88.5%)	No variation 46 (88.5%)	No variation 38 (73.1%)	Number of Rt. inf. HV (≥5 mm)	Major complication (Grade III): 13 (24.9%)
					Trifurcation 4 (7.7%)	LHA from LGA 3 (5.8%)	Trifurcation with a common confluence of right posterior and anterior 9 (17.3%)	0: 22 (42.3%)	Biliary problem: 7 (13.5%)
					RAPV from LPV 2 (3.8%)	RHA from SMA 2 (3.8%)	RPHD drains into LHD 2 (3.8%)	1: 16 (30.8%)	30-d mortality: 1 (1.9%)
						Accessory LHA from LGA 1 (1.9%)	RPHD drains directly into the CHD 2 (3.8%)	2: 13 (25.0%)	
							Branch of LHD drain into RHD 1 (1.9%)	3: 1 (1.9%)	
Chen *et al.* (64)	13	‘13–‘15	RH	Retrospective	RAPV from the proximal LPV 1 (7.6%)	Middle HA 2 (15.3%)	Trifurcation 1 (7.6%)	No	Grade I and II: 0 (0%)
						Replaced RHA from SMA 2 (15.3%)	Early bifurcation of the right intrahepatic duct 1 (7.6%)		Grade III and IV: 2 (15.3%)
									Hepatic artery thrombosis: 1 (7.6%)
Broering *et al.* (65)	35	‘15–‘19	RH	Retrospective	N.a.	Double arterial supply 3 (8.6%)	Two or more BDs 15 (43%)	N.a.	Overall: 17 (49%)
									I e II: 5 (14%)
									III e V: 12 (34%); sepsis: 8 (23%)
									Re-LT: 1 (3%)

LLS, left lateral sectionectomy; RH, right hepatectomy; RAPV, right anterior portal vein; LPV, left portal vein; N.a., not applicable; LHA, left hepatic artery; LGA, left gastric artery; RHA, right hepatic artery; SMA, superior mesenteric artery; HA, hepatic artery; RPHD, right posterior hepatic duct; LHD, left hepatic duct; CHD, common hepatic duct; RHD, right hepatic duct; BD, bile duct; Rt. inf., right inferior; HV, hepatic vein; LT, liver transplant.

Table 2 Perioperative donor outcomes

Authors	Length of stay (days)	Back to work	Bile leak, n (%)	Reoperation, n (%)	Day 1 pain score	Day 3/4 pain score	AST, IU/L peak	ALT, IU/L peak
Troisi *et al.* (62)	3 [2–5]	N.a.	N.a.	0	0 [0–6]	0 [0–4]	N.a.	N.a.
Rho *et al.* (63)	9.0±2.1	N.a.	N.a.	0	5.1±1.8	4.0±1.8	245.7	296.7
Chen *et al.* (64)	7.0 [6–8]	52.9 [21–120]	1 pts (7.6)	0	3.4 [1–8]	N.a.	234.0 [122–400]	269.1 [150–519]
Broering *et al.* (65)	5.03 [3–12]	N.a.	1 pts (3.0)	0	0.89/0.8 [0–3]	0.18/0 [0–1.8]	N.a.	N.a.

AST, aspartate aminotransferase; ALT, alanine aminotransferase; N.a., not applicable.

Extremely important for the future diffusion and application of robotic technique, is the fact that the learning curve seems to be significantly shorter for robotic surgery than laparoscopy one, as showed by Chen *et al.* (30).

Bleeding control and the correct liver plane of resection are one of the most important aspects for donor safety. The minor blood loss reported in most of the donor robotic series (62-65) might be explained by increased ability for suturing combined with the sealing capacity of the harmonic scalpel.

Tsung *et al.* confirmed that the robotic approach allowed not only better control of a sudden major bleeding but also prevention of vascular injury. In their experience with minor and major MIS hepatectomies, in the laparoscopic group the control of the portal vein was usually obtained through a stapler. However, the ideal angle for stapler placement is not always easily reached with a laparoscopic approach, resulting in an increased chance of vessel injury during the procedure. In the robotic group a better vascular dissection and control with suture ligation are allowed, providing a safe and at times easier alternative to the stapling device (26).

Furthermore, the robotic approach allows the surgeon to increase the relative complexity of the liver resection performed in a shorter learning curve. Rho *et al.* reported that the inclusion criteria for donor surgery changed during the learning curve: initially robotic surgery was indicated for graft with low volume (<800 g), then larger resections were performed, followed by right lobes with the presence of inferior right hepatic veins, bile duct trifurcations or portal vein trifurcation already from the 10th case. In the *Table 5* we summarized the inclusion criteria proposed by Rho *et al*. To note, the selection of a donor with a suitable biliary and vascular anatomy is essential to achieve excellent postoperative outcome (63).

The major controversy for robotic approach regards mainly cost, safety of biliary trans-section, safety of vessel hemorrhage control and WIT in removal of the graft. As reported by most of the studies, WIT tend to be longer compared to CODRH or laparoscopic approach (62-65). Longest WIT could be explained in the context of prolonged operative time, due to longer time for docking and manipulation, especially in the right hepatic lobe mobilization compared to CODRH or laparoscopic surgery. So far, studies reported no impact in terms of increased liver enzymes or recipient complications. However, authors acknowledge that the effects of a prolonged ischemia time need further investigation.

Another concern about robotic technique is the correct identification of the anatomy of the hepatic ducts.

Most of the complications following the fully laparoscopic right hepatectomy were biliary complications. In the initial series, the hepatic duct was closed with clip or Hem-o-loc, leading to an increase in donor biliary complication (biliary fistula or stenosis). The optimal division of the hepatic duct should be performed sharply, without clipping, which can distort the stump length, shortening the hepatic duct. Ideally, donor's biliary stump should be closed with running suture. In the laparoscopic approach, with the rigidity of the instruments, this surgical time is not always easy and studies show higher biliary complications (52,62,69).

With the robotic features, a better biliary control with lower risk of damage is expected. Furthermore, the indocyanine green (ICG) fluorescent image—with the so-called Firefly technology—can be combined with robot technique. The ICG pigment is injected through the portal vein (left or right, according to the type of liver resection) and allows identifying the parenchymal demarcation line. This technique is useful to distinguish the biliary strictures, maintain the proper transection line, and determinate the optimal bile duct division point. Correct liver partition in the midplane is crucial to reduce exposure of small Glisson branches, sources of potential bleeding and bile leakage (28,56,63,70).

To note, the only conversion case reported by Rho *et al.* was due to injury to the S2 bile duct due to the absence of

Table 3 Intraoperative donors features and operative techniques

Authors	Type of robot	Device for resection	Technique of transection	Total OP time, min	Console time, min	Blood loss, mL	IO transfusion (%)	Graft weight (g)	Conversion to open surgery, n (%)	Initial WIT, min	ICG	Stump artery control	Stump portal control	Stump vein control	Graft extraction
Troisi *et al.* (62)	Xi da Vinci	Maryland bipolar + harmonic scalpel	T-U	290±45	N.a.	50 (30–250)	0 (0%)	223±41	0 (0%)	7 (5–18)	Yes	Hem-O-lock	45 mm vascular robotic	45 mm vascular robotic	Pfannestiel
Rho *et al.* (63)	Xi da Vinci	Maryland bipolar + harmonic scalpel	Rubber band suspension	493.6±91	420.2±88	109±101.5	0 (0%)	718.9±104.3	1 (1.9%) Injury to the S2 bile duct	15.7±6.4	Yes	Tie + Double Hem-o-lok	Double Hem-o-lok	Multifire Endo TA	Pfannestiel
Chen *et al.* (64)	N.a.	Harmonic scalpel + bipolar	Ties over the bilateral sides of the transection line percutaneously fixed	658 (498–768)	596 (353–753)	169 (50–500)	0 (0%)	617.7 (350–820)	0 (0%)	9.5 (8–15)	Yes	Double clipping	Double clipping	Endo GIA	Pfannestiel
Broering *et al.* (65)	Xi da Vinci	Harmonic scalpel	Two traction stitches on side of the transection line and percutaneously fixed by rubber shots	504±73.5	N.a.	250 (100–800)	0 (0%)	701±148	0 (0%)	8 (5–15)	Yes	Double Hem-o-lok	35-mm vascular robotic stapler	60-mm Endo GIA	Pfannestiel

OP, operative time; IO, intraoperative; WIT, warm ischemia time; ICG, indocyanine green; T-U, trans-umbilical approach; N.a., not applicable.

Table 4 Donor's complications

Authors	N.	Overall	C-D 1	C-D 2	C-D 3a	C-D 3b	C-D 4	C-D 5	CCI
Troisi *et al.* (62)	25	0	0	0	0	0	0	0	N.a.
Rho *et al.* (63)	52	12 (23.1%)	6 (11.5%)	4 (7.7%)	1 (1.9%)	0 (0.0%)	1 (1.9%)*	0	22.7±25.6
Chen *et al.* (64)	13	1 (7.7%)	0		1 (7.7%)			0	N.a.
Broering *et al.* (65)	35	2 (6%)	2 (6%)		0				N.a.

*, hepatic artery bleeding (dislodgement of the Hem-o-lok clips). C-D, Clavien-Dindo classification; CCI, Charlson comorbidity index; N.a., not applicable.

Table 5 Indications for robotic living donor right hepatectomy proposed by Rho *et al.* (63)

Variables	Initial indications	Final indications
Right hepatic artery	One hepatic artery Common length >1 cm	No variation
Right portal vein	Common length >1 cm	Common length >1 cm Some variants are acceptable
Right bile duct	Common length >0.5 cm	Common length >0.5 cm Some variants are acceptable
Right inferior hepatic vein	No inferior RIHV	No limitation
Middle hepatic vein branch (V5 and V8)	No limitation	No limitation
Estimated graft volume	<800 g	<1,000 g

RIHV, right inferior hepatic vein.

ICG cholangiogram guidance (63).

Data from the studies about biliary injury, however, are still controversial. Suh *et al.* reported in the robotic group a higher ratio of multiple bile duct openings compared to the laparoscopic group (56). Troisi *et al.* reported similar results with a slightly increased incidence of multiple bile ducts in the graft in the robotic group. In fact these authors related their results not to robotic approach, but rather to the transection technique (trans-umbilical transection line) (62). The transection technique, as in liver resection for liver tumor, can interfere in the incidence of vascular and biliary injury. One limitation of the robotic approach is the absence of device dedicated to liver surgery, that can affect the rate of vascular and biliary damage. The cavitron ultrasonic surgical aspirator (CUSA), that could ameliorate the parenchyma partition, is still lacking, and the harmonic scalpel available is short with no endowrist.

Approach to the robotic surgery

Robotic liver resection is safe and feasible in the hand of surgeons with high expertise in laparoscopic and robotic surgery applied both to hepatobiliary and transplant surgery. Initial data showed that, compared to the open and laparoscopic approach, the robotic approach is associated with lower blood loss and improvement in post-operative pain control. However, these results must be evaluated in the context of a progressive and still ongoing learning curve, with most of them still not plateaued.

Iuppa *et al.* reported some recommendations for the surgeons who are planning to begin a robotic living donor program: the surgeon and the team should have an adequate expertise in open and laparoscopic hepatobiliary surgery along with a strong experience with living donation (71). However, there is no high level of evidence that a strong expertise in laparoscopic surgery is a necessary preliminary step to proficiently approach living donation with the robot.

It is important to note, however, that most of successful robotic living donor hepatectomy series come as a consequence of a long and step-by-step practice with open and laparoscopic liver surgery, starting from non-anatomic laparoscopic resection, left lateral resection, left hepatectomy and ending to laparoscopic right hepatectomy for liver tumor.

The application of robotic technique in the LDLT is the sum of experience in liver transplant, hepatobiliary surgery and MIS and an appropriate training is necessary in these three disciplines (72).

Liver mobilization and hilar dissection are usually reported to be an easy procedure, while liver transection without Pringle maneuver, bile duct division and organ harvesting with short ischemia time are the main concerns in the robotic approach.

Especially in the initial learning curve, a long operative time is expected, and the selection of a suitable donor is important as well.

Donor and recipient correct selection is crucial to reduce the morbidity and the robotic complications. To reduce the vascular and biliary issues, a permissive anatomy is mandatory, with a correct pre-operative evaluation. For biliary anatomy, an excellent magnetic resonance cholangiopancreatography (MRCP) is necessary and 3-D reconstructions can help to understand better the vascular anatomy. The use of real-time ICG seems to be crucial for correctly identifying the biliary tree, planning the exact plane of resection, and setting optimal bile duct division point.

The initial strict selection criteria, after cumulative surgical experience, can be expanded to larger graft and vascular variants, as shown by Rho *et al.* (63). Attempting a robotic hepatectomy in donors with unfavorable vascular or biliary anatomy may expose them to a high rate of intra and postoperative complications.

Conclusions

To date, data doesn't support the superiority of robotic approach versus laparoscopic or open method in living donor hepatectomy. Robotic hepatectomy performed in properly selected living donors and by teams with high expertise in both MSI liver surgery and LDLT is safe and feasible. Robotic hepatectomy procedure, especially RRLDH, is still not standardized, as well as the correct donor selection and surgical technique; further investigations to address these concerns are mandatory. Laparoscopic and robotic donor hepatectomy should not be considered as opposed but complementary choices, based on specific donors and recipients features.

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Footnote

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