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Robotic surgery in the aspect of liver transplantation

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Abstract

Introduction. *Almost 60 years have passed since the first liver transplant performed by Thomas Starzl. During this time, medical technologies have gradually improved, which has made it possible to use more and more new methods and approaches in this type of medical care. One of the new techniques of recent decades is robotic surgery, which is gradually being introduced into medical practice, including in the field of transplant medicine.*

Objective. *The purpose of writing this review was to summarize knowledge and describe the current status of development of robotic surgery in the aspect of liver transplantation, namely: liver resection in donors, as well as graft implantation in the recipient.*

Material and methods. *The review includes foreign and domestic publications on minimally invasive donor liver surgery. Publications on the topic of robotic liver resection in the aspect of liver transplantation were also processed.*

Conclusion. *Robotic surgery using advanced robotic systems represents the next step in the development of minimally invasive technologies in liver* *transplantation. Robotic systems provide more precise and dexterous control of instruments, allowing surgeons to perform complex procedures with greater precision and less risk to patients. However, the robotic approach is still very limited in geographical distribution and requires much more experience than laparoscopy. The upcoming introduction of new robotic systems that support haptic feedback or cavitronic ultrasonic surgical aspirators will further promote a widespread adoption of robotic liver resection in liver donors and liver recipients.*

Keywords: liver transplantation, minimally invasive surgery, robotic surgery, liver

Conflict of interests Author declares no conflict of interest

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CD, Clavien-Dindo (Classification of complications)
LD, left lobe
LLS, left lateral sector
RL, right lobe

Introduction

Minimally invasive liver surgery is advancing, robotic surgery is gaining experience in Russia, and Europe is adopting the experience of Asia and the Middle East [1, 2]. In the aspect of liver transplantation, the technique of laparoscopic removal of liver fragments for subsequent transplantation has become widely used in recent 20 years. The first pure laparoscopic removal of the left lateral section (LLS) of the liver from a living donor was performed by the French surgeon Daniel Cherqui in 2002.

Moreover, despite the fact that minimally invasive liver resection was developed using various options (hand-assisted laparoscopic surgery, laparoscopic-assisted, pure laparoscopic); the procedure for harvesting the LLS from a living donor was initially demonstrated exclusively as a completely laparoscopic technique. The operation at all stages (mobilization, isolation of vessels, transection of the parenchyma) was performed as a laparoscopic non-hand-assisted procedure and the graft was removed through a small suprapubic incision [3]. Laparoscopic left hemihepatectomy in a living donor was demonstrated by R.I. Troisi in 2013 [4]. Pure laparoscopic right hemihepatectomy in a living donor was first demonstrated in 2010 in South Korea, but the results of the study were presented only in 2014 [5], so it is believed that the first right hemihepatectomy was performed by the French surgeon O. Soubrane in 2013, since the Korean surgeon H. S. Han had not published his results [6, 7]. Nevertheless, the technique of this operation has been successfully implemented in Asian countries, primarily in Japan and South Korea, where living donation traditionally prevails over posthumous donation [6–8]. Meanwhile, the surgical technique differed greatly from hospital to hospital, both in the placement of trocars and in the sequence of surgical stages [9, 10]. Studies have also shown that the minimally invasive surgical technique for removing liver fragments did not affect the number of complications in recipients [6, 11]. In the Russian Federation, a laparoscopic removal of a liver fragment from a donor was performed at V.I. Shumakov Federal Research Center of Transplantology and Artificial Organs in 2016 [12–14]. Laparoscopic removal of the liver right lobe from a living related donor in the Russian Federation was first demonstrated by S.E. Voskanyan in 2017 [10]. Currently, the Russian Federation has accumulated significant experience (more than 300 operations) of laparoscopic liver resections in living donors [6, 10, 12–15]. Also in the Russian Federation, a simultaneous laparoscopic harvesting of a kidney and a liver fragment from the same living related donor was performed for the first time in the world [16].

A robotic-assisted resection for liver donation is much less common than the laparoscopic resection, but is considered safe and feasible in hands of experienced specialists. However, in addition to robotic liver resection, reports of successful robotic hepatectomy and implantation of liver grafts have begun appearing. This review describes the current status of the robotic surgery development in the area of liver transplantation.

Robotic liver resection in donors

The first robotic liver transplant was performed by an Italian surgeon P.C. Giulianotti et al. in 2012. The operation was performed using the Da Vinci Robotic Surgical System (Intuitive Surgical, USA) to a 53-year-old man whose liver right lobe was removed for subsequent transplantation to his 61-year-old brother [19]. The operation was successful, and the donor was discharged home without complications with a normally functioning left liver lobe on the 8th postoperative day. Thus, P.C. Giulianotti demonstrated the feasibility of this procedure, although there had been considerable debate in the surgical community regarding the widespread implementation of this method into routine practice [19, 20].

In 2017, M.H. Liao et al. reported the first successful case of robotic lateral sectorectomy in a living donor for transplantation to a 7-month-old boy suffering from biliary atresia [21]. In 2021 R.I. Troisi compared 25 robotic LLS removals from living donors with laparoscopic ones. Blood loss, the need for postoperative pain relief, and hospital stay were reduced in the robot-assisted donor group, while the number of complications remained similar to that in the laparoscopic group [22].

In 2016, P.D. Chen et al. described their results from the first small series of 13 robot-assisted right hemihepatectomies, showing that the robotic approach was safe and feasible. The number of postoperative complications was similar to that for open surgery [23].

A more interesting study was conducted by D.C. Broering et al. They compared the results of open and robot-assisted right hemihepatectomy in living donors, eliminating systematic differences between the compared groups using the method of propensity score matching. Between 2015 and 2019, 35 robotic-assisted and 70 open surgeries were performed. Pseudorandomization reduced heterogeneity between the two groups and avoided bias in selecting an anatomically favorable donor for the robotic resection group. With a similar number of postoperative complications according to the Clavien–Dindo classification, in the group of donors who were operated on using a robot, a shorter hospital stay after surgery was observed. It was also shown that intraoperative blood loss was significantly lower in the robot-assisted surgery group. There was less use of analgesics in donors undergoing robot-assisted surgery. However, in the group of robot-assisted operations, the average operating time for donors was longer. However, the authors noted that the surgery time decreased significantly from operation to operation, which indicated the accumulation of experience [24].

In 2020 S.Y. Rho et al. in their study compared donors who underwent right hemihepatectomy in three different ways: open, laparoscopic, and robotic. The study showed longer robotic surgery times compared to other approaches, but less blood loss and lower rates of postoperative pain. The authors also analyzed the learning curve depending on the number of operations performed, showing that the total surgery time decreased with acquiring skills. The primary warm ischemia time in the robot-assisted resection group was significantly longer, but the authors explained that by the fact that donors with more complex anatomical peculiarities were gradually included in the study [25].

Compared to the laparoscopic approach, the evolution of robotic surgery in liver donor surgery has been slow. Potential advantages of the robotic method include an expanded and more stable view of the surgical field, as well as greater accuracy of movements at manipulations. Surgical manipulators of Da Vinci system can rotate in all directions, allowing for a wider range of motion than the human hand. This allows manipulation and suturing in the subhepatic space at angles that are not possible with conventional instruments [26]. Of the minuses, the surgeon does not have tactile feedback; although in the latest, 5th generation, the Da Vinci systems promise to solve this problem [27]. Also, the surgery success depends on the level of training of the assistant, who changes the instruments of the robot during the parenchyma dissection [26].

Recent studies have shown that robotic liver resection in donors is feasible and produces similar short-term results as laparoscopic surgery, but at higher costs, since health insurance does not usually cover such advanced procedures [28]. Another obstacle to the spread of this technique is the need for high specialization of the center and the availability of surgical instruments, since during robotic liver surgery only ultrasonic scalpels, Hem-o-lock clips and staplers can be used; it is not possible to use cavitron ultrasonic dissectors [29].

Two studies comparing robotic liver resection and an open donor resection showed noninferiority of the robot- assisted approach in terms of complications and intraoperative blood loss [22, 29].

There is currently no evidence to suggest that the robotic approach is superior to the open or laparoscopic approach. R. I. Troisi et al. did not find any extraordinary result justifying the higher cost of the robotic approach compared to the laparoscopic one [22]. The investigators also emphasized that conversion with robotic resection takes longer than with the laparoscopic approach. Therefore, it is critical to use all robotic techniques available to control unexpected bleeding before the conversion.

Regarding the learning curve in robotic donor surgery, D.C. Broering et al. claim that robotic hemihepatectomy has a short learning curve: the mastery stage is achieved in 15 procedures [30]. P.D. Chen et al. took a more measured approach to the training and divided the curve into three phases: a novice surgeon (1–15 operations); a trained surgeon (15–25 operations); and an experienced surgeon (25–52 operations). The effect of training was demonstrated by reduced surgery duration time and shorter hospital stay for donors after the first phase of training. After the second phase of training, blood loss decreased. The authors also note that the presence of a dual robot control console offers a safe form of training, since the supervisor (teacher) can assist the surgeon during the operation and take control if necessary [23, 29].

The greatest experience in robot-assisted liver resection in donors was demonstrated by surgeon M. Schulze et al. There were 177 LLS, 112 left lobe, and 212 right lobe removals reported using robotic technology [2]. The total experience is presented in the table.

Table. Results of robot-assisted removal of liver fragments in various transplant centers

Author	Number of surgeries, n	Removed fragment	Surgery duration, minutes (range)	Blood loss, mL	Conversions, n (%)	Learning curve, number of surgeries or effect	Complications (C-D), number	Hospital length of stay, days (range)
P.D. Chen et al., 2016 [23]	16	RL	596 (353–753)	169 (50–500)	0	15	Grade IIIa – 1	7 (6–8)
D.C. Broering et al., 2020 [24]	35	RL	504±73.5	250 (100–800)	0	15	Grades I and II – 2	5.3 (3–12)
S.T. Binoj et al, 2020 [31]	51	RL	536.8±73.4	530,39±222,72	0	Not described	Not described	8.27±3.0
S.Y. Rho et al., 2020 [25]	52	RL	493,6	109,8	2 (3,8%)	Decrease of surgery duration	Grades I and II – 8 Grades IIIa and IIIb – 2	5±3.0
D.C. Broering et al., 2020 [30]	175	LLS – 61 LL – 34 RL – 80	424 (177–693)	138.1 (20–1000)	2 (1,14%)	15	Grades I and II – 12	4.3 (2–22)
R.I. Troisi et al., 2021 [22]	25	LLS	290	100	0	Decrease of surgery duration	0	3±0.3
M. Schulze et al., 2022 [2]	501	LLC – 177 LD – 112 PD – 212	406 (176–692)	60 (20–800)	0	Not described	Grade I and II – 31 Grade IIIa- 1	4 (2–22)

Notes: LLS, left lateral sector; LL, left lobe; RL, right lobe; C-D, Clavien-Dindo (classification of complications).

Moreover, a meta-analysis conducted by E.P. Lincango Naranjo et al. showed that robotic donor liver resection might be a safe approach for living donor liver donation compared with conventional and laparoscopic methods. However, the results of their study should be interpreted with caution because the number of studies examined was small and all studies in the meta-analysis included predominantly Asian patients [32]. The authors note that further studies in this area are needed to confirm these results and draw reliable conclusions.

The use of minimally invasive techniques in living liver donors does not in any way affect the number of organs available for transplantation from posthumous donors. However, the use of robotic and laparoscopic techniques could potentially lead to an increase in the number of living donors. According to the data cited in their studies, K.O. Semash and A.R. Monakhov reported that when communicating with potential donors, they were more willing to agree to donate when they learned about the possibility of minimally invasive surgery [6, 14]. There are no statistically significant data on the effect of minimally invasive techniques on increasing the number of related donors described in the literature. L. Tran concludes in his work that despite the potential for faster postoperative recovery and the additional attractiveness for potential living donors due to the good cosmetic effect of a minimally invasive approach, the barrier to entry for medical institutions in terms of equipment costs and training of surgeons is too high compared to the traditional methods of liver graft harvesting, which, in turn, may present an obstacle to an increase in the number of related liver transplants [17]. At the same time, N.A. Vijai in his work has reported that the benefits of minimally invasive surgery for donors include cosmetic effect, reduced post-operative pain and shorter hospital stay after surgery, which are important from the donor rehabilitation point of view, and these benefits could potentially lead to an increase in the number of liver transplants from a living donor [18].

Robotic hepatectomy and graft implantation

Hepatectomy is the first preparatory stage of liver transplantation, which involves the complete removal of recipient's liver. For many years, this has been a complex and invasive procedure, usually technically demanding for the surgeon. The first step to robot-assisted hepatectomy was laparoscopic hepatectomy. Thus, surgeon S. Dokmak in 2020 was the first to report a successful laparoscopic hepatectomy in a 52-year-old patient, who subsequently underwent a traditional liver transplantation for metastases of a neuroendocrine tumor. The postoperative period was uneventful [33, 34].

Korean surgeons, who had the largest experience in laparoscopic donor liver resection (more than 500 right donor hemihepatectomies), decided to gradually develop robotic surgery in liver transplantation. So, based on their experience of performing laparoscopic donor procedures, as well as the knowledge of liver mobilization and preservation of hepatoduodenal vascular structures and bile ducts, they began to attempt laparoscopic liver mobilization in recipients. Laparoscopic hepatectomy was then performed in 2021, followed by conventional graft implantation [35]. Following this, the authors reported that they decided to expand their surgical technique to hybrid graft implantation (robotic and laparoscopic methods). Thus, caval and portal anastomoses were performed using laparoscopic technology, and arterial and biliary anastomoses were performed using a robot [36]. Further, a group of the same authors demonstrated their first experience of robot-assisted liver graft implantation after a pure laparoscopic hemihepatectomy [37]. The surgery duration was 12 hours and 20 minutes, and the blood loss was 3600 ml. The authors reported that the bleeding intensity during such operations depended on such factors as the patient's condition severity at the time of transplantation, and surgical factors, as well. Most of the blood loss in the cases described above, according to the authors, was the result of diffuse bleeding associated with cirrhotic coagulopathy. However, the authors suggested that if the surgical procedure was quicker and the surgery duration time was shortened, there would be less blood loss.

In 2024 D.C. Broering et al. demonstrated the first mini-series of robotic hepatectomies in three patients followed by robotic graft implantation. In two of these patients, the indication for transplantation was fatty liver disease, and in one, liver cirrhosis as a result of viral hepatitis C [38]. The authors noted that they had encountered some technical difficulties during those operations. Thus, it was noted that a cirrhotic liver was more difficult to be mobilized and subjected to traction. The surgeons used special soft sponges to mobilize and remove such a liver to avoid trauma and bleeding caused by the instruments. The authors also stated that the clamp configuration for the inferior vena cava was not ideal, and they are currently working to develop robust and reliable fully robotic clamps for it. Another problem was that the portal vein of the right liver lobe graft was relatively short; and to avoid tension on the anastomosis, special sponges were placed behind the graft to more congruently position the anastomosed vessels. Despite all the technical difficulties described, the rehabilitation of the patients was uneventful, and all of them were discharged home without complications on the 13th postoperative day.

All cases of minimally invasive hepatectomy and graft implantation that were described above were referred to transplantation from living donors. However, American surgeons demonstrated a completely laparoscopic hepatectomy and implantation of a whole cadaveric liver in March 2024. The operation was performed on a 62-year-old man with liver cirrhosis due to hepatitis C, complicated by hepatocellular carcinoma. The total surgery duration operative time was 8 hours 30 minutes, and the hepatectomy took 3 hours 30 minutes. The patient recovered without early graft dysfunction or surgical complications [39].

G. Iuppa et al. described recommendations for surgeons planning to initiate a robotic liver transplantation program. Thus, the surgeon and his team should have sufficient experience in open and laparoscopic hepatobiliary surgery, as well as extensive experience in related donor liver resections and experience in liver transplantation [40]. However, the authors note that there is no convincing evidence that significant experience in laparoscopic surgery is a necessary preliminary step for skillful use of the robot. Also, according to the authors, an important aspect of the development of this area will be the standardization of surgical techniques.

Robotic hepatectomy and implantation are feasible in the hands of the surgeons highly experienced in laparoscopic and robotic surgery, especially those with extensive experience in hepatobiliary surgery. However, it is too early to talk about safety, since this approach is only at the implementation stage. Initial data showed that, when compared with open and laparoscopic approaches, the robotic surgery in recipients is associated with reduced postoperative pain. It has not yet been possible to demonstrate significant surgical benefits for the recipient, such as the reduction in blood loss. However, these results must be assessed in the context of a progressive and ongoing learning curve, since the number of similar operations is very limited and there are no data on long-term results.

Meanwhile, suboptimal long-term results of liver transplantation are directly related to the minimally invasive technique of liver implantation, which is associated with increased reperfusion injury of the graft due to the prolongation of secondary warm ischemia time, which can cause biliary stenosis and other complications in the long-term postoperative period. The only data on long-term results of laparoscopic liver implantation were reported by S. Dokmak et al. [34]. Thus, during the follow-up period, the median of which was 8 months, the recipients did not experience any long-term complications. As for recipients who underwent liver transplantation using robotic technology, there are currently no large-scale studies of data on long-term results, and all publications on this topic cover only the postoperative period, which in all cases was uneventful. There is only one study on this subject by A.S. Khan et al., which covers a follow-up period of 6 months in one patient. During this follow-up period, the recipient did not develop post-transplant complications [39].

Conclusion

Robotic surgery, using advanced robotic systems, represents the next step in the development of minimally invasive technologies in liver transplantation. Robotic systems provide more precise and dexterous control of instruments, allowing surgeons to perform complex procedures with greater precision and a less risk to patients. However, the robotic approach is still very limited in geographical distribution and requires much more experience than laparoscopy. The upcoming implementationn of new robotic systems that support haptic feedback, or cavitronic ultrasonic surgical dissectors, will further promote robotic liver resection in liver donors and liver recipients.

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