Clinical Practice Guideline

Chinese guidelines for minimally invasive donor hepatectomy in living donor liver transplantation (2024 edition)

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Background: Minimally invasive surgeries are increasingly central to modern medicine, particularly in liver transplantation. These techniques, which offer reduced trauma, precise operations, minimal bleeding, and swift recovery, are, however, unevenly adopted across China. Only a limited number of centers routinely perform minimally invasive donor hepatectomies, indicating a significant imbalance in the development and application of these advanced procedures. Additionally, there lacks a set of standardized guidelines that are

tailored to meet China's unique healthcare challenges and conditions.
Methods: In August 2023, the Branch of Organ Transplant of Chinese Medical Association and the Branch of Organ Transplant Physicians of Chinese Medical Doctor Association convened a group of national liver transplantation experts to establish a guideline development committee. This committee conducted a thorough review of relevant literature, evaluated existing guidelines and consensus, and assessed factors such as the evidence base, patient preferences, and the cost-effectiveness of interventions within China. After multiple rounds of discussions, both online and offline, the committee finalized the guidelines.
Results: This collaborative effort led to the creation of the "Chinese guidelines for minimally invasive donor hepatectomy in living donor liver transplantation (2024 edition)". These guidelines address crucial aspects such as the safety and advantages of minimally invasive surgery for living donor liver transplantation, donor selection criteria, anesthesia strategies, surgical technical details, and learning curves associated with these procedures, resulting in a comprehensive set of 26 recommendations.
Conclusions: The formulation of these guidelines represents a significant advancement towards standardizing minimally invasive liver transplantation surgeries in China. They are designed to enhance outcomes for both donors and recipients by synthesizing expert consensus with contemporary research and clinical practices. Moreover, they serve as a crucial reference for surgeons and medical institutions, promoting the refinement and adoption of minimally invasive surgical techniques in liver transplantation.

Keywords: Living donor liver transplantation; donor; minimally invasive surgery; guideline

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Introduction

Organ shortage remains a challenge in the development of liver transplantation. Living donor liver transplantation is a widely recognized and effective method for treating end-stage liver disease and for expanding the pool of available livers. Given that donors are healthy individuals who undergo surgery for non-pathological reasons, their quality of life, including postoperative pain, aesthetics, and hospital experience, should be carefully considered and subjected to stringent requirements. Minimally invasive surgical techniques with reduced trauma and invasiveness can alleviate pain, shorten recovery periods, and reduce postoperative complications. Achieving optimal surgical outcomes necessitates the use of cutting-edge surgical equipment and precise operative skills during this procedure. Since 2002, when Cherqui *et al.* (1) successfully performed the first laparoscopic left lateral sectionectomy from a living donor for pediatric liver transplantation in France, various minimally invasive techniques have gained widespread adoption globally and have gradually become the standard procedure for pediatric liver transplantation (2). However, adult living donor liver transplantation has progressed more slowly because of the larger liver volume required and increased surgical complexity. In 2006, Koffron *et al.* (3) pioneered laparoscopy-assisted living-donor right hepatectomy in the United States. In 2009, Kim *et al.* (4) from Korea reported a living donor right hepatectomy through a small upper midline abdominal incision. Since 2012, several teams (5-8) worldwide have reported successful outcomes with total laparoscopic living-donor left or right hepatectomy. In China, Yang *et al.* (9) independently reported laparoscopy-assisted living-donor right hepatectomy in 2012. In 2016, Li *et al.* (10) performed a total laparoscopic living donor right hepatectomy in China. These innovative techniques and developments have led to the accumulation of valuable experience for similar procedures in the future. Furthermore, with the rapid advancements in robotic technology, Giulianotti *et al.* (11) reported the first robot-assisted donor right hepatectomy in 2012. Subsequently, institutions in China, including the West China Hospital of Sichuan University, Huashan Hospital affiliated with Fudan University, and Tianjin First Central Hospital, have explored robot-assisted hepatectomy from living donors. Robotic technology has also been used in surgeries of living liver transplant donors.

Although many centers in China perform living donor liver transplantation, the number of centers that routinely perform minimally invasive donor hepatectomies is relatively small. Compared with top international centers (12-14), there remains a gap. Therefore, to foster a more standardized, safe, and effective development of minimally invasive surgery in various living donor liver transplant centers in China. In August 2023, in Chongqing, China, the Branch of Organ Transplant of Chinese Medical Association and the Branch of Organ Transplant Physicians of Chinese Medical Doctor Association organized national liver transplantation experts to establish a guideline development committee to begin formulating the "Chinese guidelines for minimally invasive donor hepatectomy in living donor liver transplantation (2024 edition)" (hereinafter referred to as "this guideline"). The committee identified the safety and advantages of minimally invasive surgery for living donor liver transplantation, donor selection criteria, anesthesia strategies, surgical technical details, and learning curves as the main topics for discussion. The committee members conducted systematic reviews in PubMed, Embase, Cochrane, and three Chinese databases (CNKI, Wanfang, and CBM) based on these topics. The evidence grading of evidence-based medicine adopted in this guideline mainly refers to the "Oxford Centre for Evidence-Based Medicine: Levels of Evidence (2001 Edition)" (15), and the strength of the recommendation mainly refers to the "Grades of Recommendation, Assessment, Development, and Evaluation (GRADE)" system (16) recommendation grading. Based on the evidence and its quality, the expert group developed corresponding recommendations for each key discussion area, and these were revised after discussion in two online meetings (December 2023 and January 2024). Finally, all content was revised and approved after two offline discussions by members of the Branch of Organ Transplant of Chinese Medical Association and the Branch of Organ Transplant Physicians of Chinese Medical Doctor Association. We present this article in accordance with the RIGHT reporting checklist (available at https://hbsn.amegroups.com/article/view/10.21037/hbsn-24-329/rc).

Highlight box

Key recommendations

- The existing minimally invasive surgical techniques for donor hepatectomy are safe and feasible. They can reduce the incidence of postoperative complications for the donors, and do not significantly impact the prognosis for the recipients.
- More careful preoperative evaluations are needed for living liver transplant donors undergoing minimally invasive surgery to ensure their safety.
- For transplant centers that are still in the early stages, starting with a small upper midline incision living donor hepatectomy or laparoscopic-assisted donor hepatectomy is recommended. Under the core premise of ensuring donor safety, they can gradually transition to total laparoscopic or robotic donor hepatectomy.
- In minimally invasive surgery for donor hepatectomy, any event that may jeopardize the donor's safety or graft integrity should prompt a rapid conversion to open surgery.
- The implementation of minimally invasive surgery for donor hepatectomy requires physicians with extensive experience in minimally invasive and open living donor hepatectomy.

What was recommended and what is new?

- Previous guidelines focused only on donor outcomes, recipient outcomes, techniques, training and certification.
- Our recommendations are based on the specific conditions in China, covering key factors such as the safety and advantages of minimally invasive surgery for donor hepatectomy, donor selection criteria, anesthesia strategies, surgical technical details, and learning curves.

What is the implication, and what should change now?

- This guidelines summarizes the latest research on minimally invasive surgery for donor hepatectomy, with a particular focus on the implementation of these techniques in China.
- Future research topics include optimization of minimally invasive surgical techniques for living donors, comparison between robotic donor hepatectomy and laparoscopic donor hepatectomy, with a need for high-quality randomized controlled trials to provide more robust evidence.

Safety and advantages of minimally invasive surgery for living liver transplant donors

The technique of minimally invasive surgery for living liver transplant donors has been widely used worldwide, and the types of grafts have expanded from the initial left lateral lobe to the left half of the liver and then to the right half of the liver (10,17). Compared to traditional open liver surgery, there was no statistically significant difference in the overall postoperative complication rate for minimally invasive liver surgery (18-20). In addition, minimally invasive liver surgery has advantages such as reduced intraoperative bleeding, lower incidence of postoperative incision complications, shorter total hospital stay, and better quality of life (21-23). These advantages are also reflected in the use of minimally invasive surgeries in living liver transplant donors (24-32). A meta-analysis of 31 studies (33) showed that laparoscopic left lateral donor hepatectomy was superior to open surgery in terms of blood loss [mean difference (MD) =79.03 mL], length of hospital stay (MD =2.47 days), and overall complication rate [relative risk (RR) =0.44]. Similarly, laparoscopic hemi-liver donor hepatectomy was superior to open surgery in terms of blood loss (MD =75.22 mL), length of stay (MD =1.35 days), and overall complication rate (RR =0.71); however, the operation time was longer than that of open surgery (MD =46.95 min).

Since organ donors are healthy individuals who do not need to undergo surgical trauma in the first place, their subjective satisfaction should be given more attention (34). For living donors who have undergone open surgery, 30–50% of postoperative complications are related to abdominal incisions, including incision infection, incisional hernia, chronic incision discomfort, delayed functional recovery, and psychological barriers caused by scars (30,35). A meta-analysis involving 60,829 organ donors showed that the overall incidence of postoperative complications in donors was 24.7%, with psychological complications (7.6%) and incision-related complications (5.2%) ranking as the top two (36). This makes some potential organ donors, especially young ones, hesitant before donation (1,37). The currently used minimally invasive surgery can significantly reduce the incidence of incision complications in these organ donors (14,30) while also alleviating incision pain and reducing the need for analgesics (38-42). Therefore, minimally invasive surgery for living liver transplant donors is considered an effective alternative solution for incision-related problems and psychological barriers of organ donors. These results suggest that minimally invasive surgery for living liver transplant donors is safe, feasible, and more suitable for living organ donors (24,43).

Simultaneously, minimally invasive surgery for living liver transplant donors does not significantly impact the long-term survival of recipients and the occurrence of postoperative complications (28,30,31,44-48). However, in the research conducted by Hong *et al.*, it was observed that the incidence of both early and late postoperative biliary complications in the cohort undergoing pure laparoscopic donor right hepatectomy was higher compared to the conventional donor right hepatectomy group. The researchers postulated that this could be attributed to the surgeons' propensity for excessive utilization of energy devices for biliary dissection during laparoscopic procedures (12). In contrast, another study encompassing 506 laparoscopic donor right hepatectomy cases posited that meticulous donor and recipient evaluation could effectively mitigate the incidence of biliary complications (44). Furthermore, no significant disparity was discerned in the incidence of postoperative biliary complications between the minimally invasive and open surgery groups in two separate meta-analyses (32,47).

Recommendation 1: Existing minimally invasive surgical techniques for living liver transplant donors (including small upper midline abdominal incision living donor hepatectomy, laparoscopic-assisted living donor hepatectomy, total laparoscopic living donor hepatectomy, and robotic living donor hepatectomy) are safe and feasible for donors (Evidence level: II; Recommendation strength: Strong).

Recommendation 2: Minimally invasive surgery for living liver transplant donors can reduce intraoperative bleeding, lower the incidence of postoperative complications in donors (especially incision and pulmonary complications), reduce total length of stay, and improve the quality of life and psychological satisfaction of donors (Evidence level: II; Recommendation strength: Strong).

Recommendation 3: Minimally invasive surgery for living liver transplant donors can reduce postoperative incision pain in donors and the need for analgesics (Evidence level: II; Recommendation strength: Strong).

Recommendation 4: Compared with open surgery, minimally invasive surgery for living liver transplant donors will not significantly impact the prognosis of recipients (Evidence level: II; Recommendation strength: Strong).

Evaluation and selection criteria for donors in minimally invasive surgery for living liver transplant

The safety of organ donors is the cornerstone of minimally invasive surgery for living liver transplant donors (49), and the preoperative evaluation and selection of living organ donors are of paramount importance when planning minimally invasive surgery for living liver transplant donors. The goals of evaluating living organ donors are (I) to ensure the safe procurement of a sufficient volume of the donor's liver; (II) to ensure that no donor-derived diseases are transmitted to the recipient; and (III) to ensure that organ donors are aware of the entire donation process and can overcome potential psychological consequences (50,51). Therefore, organ donors are generally required to be between the ages of 18 and 60 years, and the estimated residual liver volume should not be less than 30–35% of the initial liver volume to avoid postoperative liver dysfunction or even more serious complications (52,53). Simultaneously, to avoid the occurrence of small-for-size syndrome in recipients, a graft-to-recipient weight ratio (GRWR) of ≥0.8% is recommended (51,54). In addition, for donors with risk factors (including obesity, diabetes, and dyslipidemia) and/or imaging findings of fatty liver, liver biopsy should be performed before transplantation (55). Because a degree of macrovesicular steatosis exceeding 30% is generally believed to increase the risk of graft dysfunction in the recipient (56-59). However, using steatotic liver grafts from living donors remains controversial regarding donor safety and recipient outcome (60-62). The studies demonstrated that with approximately 20–50% macrovesicular steatosis did not compromise graft function or recipient outcomes and were safe in donors for right hepatic lobectomy (63,64). Despite all this, when frequently encountering donor candidates with mild to moderate macrovesicular steatosis in the living donor liver transplantation setting, weight loss before donation may be a good strategy for increasing donor safety and confidence in the recipient's outcome, except when the urgent condition of recipient does not allow for it (65-68).

Compared with open donor hepatectomy, minimally invasive surgery for living liver transplant donors is more technically challenging and is also undergoing rapid development, especially minimally invasive living donor right hepatectomy. Therefore, compared with open surgery, minimally invasive surgery for living liver transplant donors has stricter selection criteria, especially in terms of acquired experience, and selecting as many cases as possible is necessary to ensure the safety of organ donors and recipients to a greater extent (69). Studies (39,70,71) have shown that organ donors with anatomical variations have a significantly increased probability of postoperative complications, especially at the initial stages. Therefore, preoperative evaluation should improve abdominal three-dimensional (3D) computed tomography examination and magnetic resonance cholangiopancreatography (MRCP) as much as possible to clarify the liver anatomical structure of the donor, and in the early stage of minimally invasive technology, choose organ donors without anatomical structure variation as much as possible. Additionally, because the operating space for laparoscopic surgery is relatively small, especially for living donor right hepatectomy, choosing organ donors with a preoperative evaluation of grafts <700 g in the early stage is recommended to facilitate the exposure of the field of vision and the operation of the surgeon (72,73). In some transplant centers, to ensure the safety of organ donors and recipients, a GRWR >1% and residual liver volume >35% are required (2). With the accumulation of experience, some studies have shown that organ donors with anatomical variations can safely undergo minimally invasive surgery for living liver transplantation (44,45,74-78). Therefore, the criteria for donor selection can be expanded based on the careful judgment of the primary surgeon (69,78).

In summary, any situation that could cause severe complications during the perioperative period and the long-term recovery process of organ donors is a contraindication for living organ donation. Simultaneously, recipient safety should be considered as much as possible during the selection process.

Recommendation 5: The goals of the evaluation of living organ donors are to (I) ensure the safe procurement of a sufficient volume of the donor's liver; (II) ensure that no donor-derived diseases are transmitted to the recipient; and (III) ensure that organ donors are aware of the entire donation process and can overcome potential psychological consequences (Evidence level: II; Recommendation strength: Strong).

Recommendation 6: Abdominal 3DCT and MRCP preoperatively should be used to evaluate the volume of the donor's liver and the variation of blood vessels and bile ducts to ensure the safety of the donor and the smooth recovery of the recipient after surgery (Evidence level: II; Recommendation strength: Strong).

Recommendation 7: For transplant centers that just started performing minimally invasive surgery for donors, donors without obvious anatomical variations should be prioritized; experienced transplant centers can try to obtain transplants with anatomical variations with minimal invasion (Evidence level: II; Recommendation strength: Strong).

Anesthesia strategy for minimally invasive surgery in living liver transplant donors

The primary goal of anesthesia management is to minimize risk and effectively control pain (79). Endotracheal intubation under general anesthesia is typically performed during minimally invasive surgeries in living liver transplant donors. Depending on the extent of liver resection, epidural blockade techniques can be appropriately combined to alleviate the surgical stress response. When choosing anesthetic induction agents and muscle relaxants, drugs that are rapidly metabolized, accumulate less in the body, and have minimal impact on hepatic blood flow should be preferred. Standard anesthesia monitoring includes electrocardiography, blood oxygen saturation, invasive arterial blood pressure, body temperature, neuromuscular blockade, bispectral index, and central venous pressure monitoring. Mechanical ventilation settings should follow lung-protective strategies; that is, the tidal volume should be set at 6–8 mL/kg body weight, end-expiratory positive pressure should be maintained at

6–8 cmH_2O (1 cmH_2O = 0.098 kPa), and lung recruitment maneuvers should be intermittently applied (79-81).

During the entire surgical process, where pneumoperitoneum needs to be established, the intra-abdominal pressure is usually maintained at 12–14 mmHg (1 mmHg = 0.133 kPa). During the hepatic parenchymal transection stage, the central venous pressure should be actively controlled, usually maintained at 0–5 mmHg, to reduce bleeding from the hepatic section. After completion of hepatic parenchymal transection, aggressive fluid resuscitation should be immediately performed to restore the donor's blood volume, and the blood pressure should be adjusted back to the preoperative level (82).

In minimally invasive surgery for living liver transplant donors, owing to the establishment of carbon dioxide (CO_2) pneumoperitoneum, maintenance of low central venous pressure, and potential venous injury during the hepatic parenchymal transection process, the probability of detecting CO_2 gas embolism in donors is relatively high. Although in most cases, donors do not have obvious clinical symptoms after experiencing a gas embolism and do not require special intervention, a severe gas embolism can seriously impact the respiratory and circulatory systems and, in extreme cases, cause cardiac arrest. Therefore, early detection and timely treatment are crucial to prevent the serious consequences of gas embolism (83). Transesophageal echocardiography is recommended as a tool to monitor CO_2 gas embolism and is of great value for the early identification of gas embolism. Once a gas embolism is detected, the pressure in the abdominal cavity should be immediately reduced, and venous rupture should be quickly repaired. In necessary cases, the transition to open surgery should be considered to ensure donor safety (84).

Recommendation 8: In minimally invasive surgery where pneumoperitoneum needs to be established, a lower central venous pressure level (0–5 mmHg) should be maintained during liver graft procurement to reduce bleeding (Evidence level: III; Recommendation strength: Strong).

Recommendation 9: Transesophageal echocardiography should be used as a tool for monitoring CO_2 gas embolism (Evidence level: III; Recommendation strength: Weak).

Recommendation 10: Once a gas embolism is detected, the pressure inside the abdominal cavity should be reduced immediately, and venous rupture should be quickly repaired. In necessary cases, transitioning to open surgery should be considered to ensure the safety of the donor (Evidence level: IV; Recommendation strength: Strong).

Types and methods of minimally invasive surgery for living liver transplant donors

Types of techniques

Small upper midline incision living donor hepatectomy

This surgery involves the use of a midline incision above the navel to complete liver graft procurement. It can reduce pain and lower the incidence of incision-related complications while performing hepatic parenchymal and ductal transection under direct vision (4,85). Compared with the traditional subcostal incision, the small upper midline incision can avoid separation of the rectus abdominis without affecting the postoperative quality of life of the organ donor. However, this procedure has certain limitations. For example, owing to the narrowed field of vision, freeing the liver becomes relatively difficult and is more challenging to perform on donors with excessive body weight or large liver volume.

Laparoscopic-assisted donor hepatectomy

This type of surgery mainly includes laparoscopic-assisted, hand-assisted, and hybrid methods of donor hepatectomies. The most common method is to complete liver mobilization under laparoscopic conditions (with or without hand-assisted methods) and then make a small midline incision in the upper abdomen to complete hepatic parenchymal transection and ductal anatomical transection. This surgical method is often used as a transitional surgical method to gain experience in minimally invasive donor hepatectomy techniques in the early stages of establishing a laparoscopic donor hepatectomy center (86,87). Currently, this surgery is rarely performed at experienced transplant centers.

Total laparoscopic donor hepatectomy

This surgery involves the completion of liver mobilization, hepatic parenchymal transection, liver supply pipeline anatomy, and transection under laparoscopy, with another small incision made for specimen retrieval. This type of surgery requires high technical skills.

Robotic donor hepatectomy

Compared with laparoscopy, robotic donor hepatectomy has significant advantages in the identification of vascular structures and hepatic segment anatomy during non-injurious liver mobilization, hepatic hilum dissection, and hepatic parenchymal transection, and its learning curve is shorter. Compared with traditional laparoscopy, the robot has the following advantages: (I) stable and excellent visual effects, with up to 10 times the magnification of a microscope; (II) the best ergonomic design, equipped with tremor-free surgical instruments, with a wider range of motion and higher degrees of freedom; (III) precise anatomical ability; (IV) can suture more conveniently and quickly; and (V) clinical practice and research (88,89) have confirmed that the robot can reduce surgeon fatigue compared with traditional laparoscopy. However, robotic hepatectomy technology has certain shortcomings, including a lack of operative tactile feedback, the need for experienced assistants with laparoscopic skills, the need to reinstall the bedside robotic arm to adapt to different positions or operative holes, longer operation times, and higher operation costs (90).

Recommendation 11: Total laparoscopic donor hepatectomy and robotic donor hepatectomy have high technical requirements and should be performed in experienced transplant centers (Evidence level: II; Recommendation strength: Strong).

Recommendation 12: For transplant centers that are still in the early stages, starting with a small upper midline incision living donor hepatectomy or laparoscopic-assisted donor hepatectomy is recommended. Under the core premise of ensuring donor safety, they can gradually transition to total laparoscopic and robotic donor hepatectomies (Evidence level: II; Recommendation strength: Strong).

Surgical methods

Surgical methods included minimally invasive donor left lateral sectionectomy, minimally invasive donor right posterior sectionectomy, minimally invasive donor left hepatectomy (with or without the middle hepatic vein), and minimally invasive donor right hepatectomy (with or without the middle hepatic vein). The choice of the surgical method was based mainly on the aforementioned donor evaluation results. Ensuring donor safety is a primary requirement for minimally invasive donor hepatectomy. Therefore, with the transplant surgeons' deepening understanding of surgical instruments, surgical techniques, anatomy, and preoperative evaluation, minimally invasive donor hepatectomy has successfully transitioned from a relatively simple donor left hepatectomy or left lateral sectionectomy to a minimally invasive donor right hepatectomy (especially laparoscopic right hepatectomy). In 2022, Cho *et al.* (91) first reported the results of seven cases of laparoscopic donor right posterior sectionectomy, showing that three out of seven donors (43%) had vascular or biliary complications. In 2023, Cho *et al.* (92) included the results of a multicenter laparoscopic donor right posterior sectionectomy series in Korea (a total of 16 cases), showing that compared to laparoscopic donor right hepatectomy, the postoperative complication rate of donors who underwent laparoscopic donor right posterior sectionectomy was not statistically significant, thereby confirming its feasibility and safety. Presently, few reports exist on laparoscopic donor right posterior sectionectomy, and the implementation of this surgical procedure still requires caution.

Recommendation 13: The choice of surgical method should be based on the safety of the donor, follow a scientific learning curve, and fully consider the evaluation results of the donor and the experience and habits of the surgical team (Evidence level: II; Recommendation strength: Strong).

Surgical techniques for minimally invasive surgery for living liver transplant donors

Laparoscopic surgical equipment and instruments

Equipment

These include laparoscopic imaging systems, pneumoperitoneum devices, irrigation suction devices, and video- and image-storage devices. In terms of laparoscopic imaging systems, recent clinical randomized controlled studies and retrospective studies (14,93-101) have confirmed that 3D laparoscopy has the advantages of shortening surgical time, improving accuracy, and reducing operational errors during surgical procedures compared to 2D laparoscopy. Moreover, the literature (102) reports that the use of 3D laparoscopy can reduce intraoperative bleeding and the incidence of postoperative complications. In addition, studies (14,95) have confirmed that using a flexible 3D scope in 3D laparoscopic donor hepatectomy is more conducive to performing donor right hepatectomy. This is because the flexible 3D scope can provide a larger field of view to fully reveal the space of the right posterior lobe of the liver, and it is more convenient to handle the second hepatic portal area. In addition, compared to traditional high-definition laparoscopic systems, 4 K laparoscopic systems can provide a more high-definition and realistic surgical field of view. However, because of the short clinical application time of the 4 K laparoscopic surgical equipment, it is not seen in relevant clinical reports on laparoscopic donor hepatectomy, and its advantages need to be further studied and demonstrated.

Recommendation 14: Compared with traditional 2D laparoscopy, 3D and 4K laparoscopic equipment can help improve the comfort of the surgeon in laparoscopic donor hepatectomy; 3D laparoscopy shortens surgical time and reduces intraoperative bleeding, among which the advantage of flexible 3D scope is more prominent (Evidence level: III; Recommendation strength: Weak).

Instruments

General instruments include pneumoperitoneum needles, puncture needles, separation forceps, non-traumatic grasping forceps, scissors, needle holders, monopolar coagulation, bipolar coagulation, titanium clips, and disposable tissue closure clips, in addition to routinely prepared open hepatectomy surgical instruments. Special instruments, mainly referring to separation and liver transection instruments, include laparoscopic cutter staplers, ultrasonic scalpels, Cavitron ultrasonic surgical aspirators (CUSA), Ligasure, microwave scalpels, water-jet scalpels, and argon scalpels.

Robotic surgical equipment and instruments

Equipment

These include robotic surgical systems, mechanical surgical arms, surgical consoles, vision systems, and system control software.

Instruments

Surgical instruments include 8 mm metal cannulas and puncture devices, cross-calibrators, monopolar hooks, Maryland or Fenestrated bipolar coagulation forceps, pericardial forceps, ultrasonic scalpels, needle holders, monopolar electric scissors, and disposable tissue-closure clips. The surgeon can select other instruments according to the hospital facilities and personal preferences for use with robots and laparoscopes.

Hepatic parenchymal transection and instrument selection

Instrument selection

Minimally invasive hepatectomy requires the use of various instruments to cut the liver tissue, each with unique advantages and disadvantages. These can be flexibly selected for use based on the actual hospital situation and the proficiency of the surgeon. Because CUSA is more precise in distinguishing blood vessels and bile ducts during hepatic parenchymal transection, it is currently the most commonly used technique in laparoscopic donor hepatectomy (69,103-107). Ultrasonic scalpels are more commonly used in robotic donor hepatectomies than in laparoscopic donor hepatectomies. During the surgical process, energy instruments are first used to determine the pre-cut line of the liver and to cut open the liver capsule. Thereafter, instruments such as the CUSA are gradually used to carefully perform hepatic parenchymal transection.

Recommendation 15: When transecting the hepatic parenchyma, the surgeon can choose one or more surgical instruments according to the conditions of the hospital and personal habits, with a preference for using CUSA for hepatic parenchymal transection (Evidence level: III; Recommendation strength: Weak).

Determination of hepatectomy line

When performing donor left lateral sectionectomy, the diaphragmatic resection line is usually 1 cm to the left of the round and falciform ligaments, and the hepatic parenchyma is generally transected using a CUSA or ultrasonic scalpel. When performing hemihepatectomy or right posterior sectionectomy, the resection line should be determined by the ischemic line on the surface of the liver after the corresponding hepatic pedicle is occluded, and the course of the hepatic vein should be determined using intraoperative ultrasound. When performing a right hepatectomy without the middle hepatic vein and an enlarged left hepatectomy, the resection line should be on the right side of the ischemic line. When performing a right hepatectomy with the middle hepatic vein, the resection line should be on the left side of the ischemic line. When resecting the right posterior lobe of the donor liver, which includes the right hepatic vein, the resection line should be set inside the right anterior lobe slightly to the left of the ischemic line. Recently, there have been reports on the use of indocyanine green (ICG) to assist in the positioning of the hepatectomy line. For example, Kim *et al.* (108) reported in 2021 that using ICG fluorescence staining in laparoscopic hemihepatectomy can accurately display the left and right midplanes of the liver, shorten the operation time, and reduce the postoperative levels of alanine aminotransferase and aspartate aminotransferase. Li *et al.* (109) reported that in laparoscopic S2 left lateral monosegmentectomy, after ligating the S3 Glisson pedicle, a negative staining method was used to display the boundary between S2 and S3 and that S3 was resected to perform *in situ* volume reduction.

Recommendation 16: When transecting the hepatic parenchyma, it is recommended to use the ischemic line on the surface of the liver or ICG fluorescence staining method after *the hepatic pedicle occlusion and combine with intraoperative ultrasound to determine the resection line (Evidence level: III; Recommendation strength: Strong).*

The Pringle maneuver

Currently, commonly used energy instruments such as the CUSA and ultrasonic scalpels have extremely low work efficiency in the case of bleeding at the cut surface. Reducing bleeding shortens the time of hepatic parenchymal transection and improves efficiency. In addition, bleeding at the cut surface increases the risk of scope contamination, requiring frequent scope wiping and prolonging the operation time. Therefore, Imamura *et al.* (110) first proposed a method of intermittent hepatic pedicle occlusion in traditional open-living donor hepatectomy to improve the efficiency of hepatic parenchymal transection. A randomized controlled trial conducted by Park *et al.* (111) in 2012 showed that in the process of obtaining an open living right half of the liver, the Pringle maneuver was used, and only the postoperative peak value of alanine aminotransferase was higher than that in the non-occlusion group; however, the total bleeding volume of the donor and the postoperative length of stay were both better than those in the non-occlusion group. The organ transplant team from the West China Hospital of Sichuan University (75) also reported that the Pringle maneuver may increase the peak value of aminotransferase in the early postoperative period of the donor, but it returned to normal on the 5th day after surgery and had no effect on long-term prognosis. In 2021, the Asian-Pacific Hepato-Pancreato-Biliary Association and International Laparoscopic Liver Society asked an expert group for their opinion on whether to perform Pringle maneuver. The current consensus on intermittent hepatic pedicle occlusion is that there is no evidence to show that it has adverse effects on the graft. The Pringle maneuver helps to shorten the operation time and reduce the amount of bleeding (25). However, for minimally invasive donor left lateral sectionectomy, experienced transplant centers can use the non-occlusion liver transection method; however, there is currently insufficient evidence and further research is needed.

Recommendation 17: Currently, there is no evidence to suggest that use of Pringle maneuver during surgery has adverse effects on the graft. The Pringle maneuver helps to shorten the operation time and reduce the amount of bleeding. For minimally invasive donor left lateral sectionectomy, experienced transplant centers can use the non-occlusion liver transection method (Evidence level: IV; Recommendation strength: Weak).

Vascular anatomy and transection

Arterial anatomy and transection

Since approximately 1/5 of donors have an accessory left hepatic artery originating from the left gastric artery, it should be checked preoperatively or carefully identified intraoperatively to determine whether there is a large accessory left hepatic artery when performing a living donor left hepatectomy or left lateral sectionectomy. If present, the vessel should be protected as much as possible, and a sufficient length of the vessel should be preserved for subsequent anastomotic reconstruction. By contrast, multiple right hepatic arteries are less common and often have advantageous variations. Usually, the right hepatic artery originates from the superior mesenteric artery. Therefore, the right liver graft has a separate and longer artery, which is more conducive to anastomotic reconstruction. During intraoperative exposure of the hepatic artery anatomy, frequent clamping or violent traction of the hepatic artery should be avoided to prevent damage to the arterial intima. After systemic heparinization, when transecting the hepatic artery, ligation or vascular clamp closure can be used, and then sharp laparoscopic scissors can be used to transect the artery at an appropriate breakpoint.

Recommendation 18: During the arterial anatomy exposure process of minimally invasive donor hepatectomy, the variant arteries should be carefully and accurately identified, the operation should be performed carefully and gently to avoid causing damage to the arterial intima, and a sharp laparoscopic scissors can be used to transect the artery after ligation or vascular clamp closure of the artery (Evidence level: III; Recommendation strength: Strong).

Portal vein anatomy and transection

As far as the portal vein is concerned, there are fewer variations in the left branch of the portal vein; therefore, it is usually easier to obtain sufficient portal vein length for the left graft. If multiple branches of the right portal vein are present, the resection risk and transection length should be fully evaluated for subsequent reconstruction. In minimally invasive donor hepatectomies, a disposable tissue closure clip or vascular cutting closure device can be used for portal vein transection. However, compared with the traditional open surgery cut-suture method, the above methods lose an additional 2–3 mm of vessel length; therefore, more portal vein transection margins should be left during the operation.

Recommendation 19: During the portal vein anatomy exposure process in minimally invasive donor hepatectomy, variations should be carefully and accurately identified, and a disposable tissue closure clip or vascular cutting closure device should be used for portal vein branch transection. The impact of the above methods on the loss of vessel length should be fully considered (Evidence level: III; Recommendation strength: Strong).

Hepatic vein anatomy and transection

Evaluating the course of the hepatic vein and possible variations through CT, MRI, and 3D imaging before surgery is recommended, and intraoperative ultrasound can better locate the hepatic vein. The necessary anatomy and exposure of the hepatic vein are performed according to the type of graft. The middle hepatic vein is an important structure that must be fully dissected during the splitting of the hemi-liver graft. The key operation is to accurately locate and protect the main trunk of the middle hepatic vein while properly exposing and transecting the middle hepatic vein branch on the side to be cut. Additionally, the use of low central venous pressure technology during surgery can effectively prevent and control venous bleeding. Because during the operation under laparoscopy or robot, after the main trunk of the hepatic vein is transected, it is difficult to control the venous end. To prevent the risk of major bleeding caused by the slipping of the vascular remnant, the use of a vascular cutter stapler to transect a large hepatic vein is recommended.

Biliary anatomy and transection

Biliary management is a major challenge in minimally invasive living-donor hepatectomy (112). It is generally believed that the anatomy of the bile duct, determination of the bile duct transection point, and treatment of bile duct remnants are crucial for the prevention of postoperative biliary complications in recipients. Generally, the left bile duct is longer and can be handled more properly, whereas the right bile duct has more variations, and the convergence position of the right anterior and right posterior hepatic ducts is uncertain. Therefore, management of the right liver graft bile duct is difficult, and its complexity is far higher than that of the left liver graft.

Biliary anatomy

Regarding bile duct anatomy in minimally invasive surgeries, surgeons are more likely to use energy instruments near the bile duct. This heat transfer may damage the endothelium and affect the microvessels around the bile duct, leading to ischemic injury of the bile duct (12,39). Therefore, when dissecting the first hepatic portal, energy instruments should be used cautiously, and excessive dissection should be avoided to reduce the occurrence of biliary complications.

Biliary transection

During biliary transection, if the surgeon places the transection point closer to the donor side, donor safety may be jeopardized, thereby increasing the risk of postoperative biliary complications. If the transection point is placed closer to the graft side, out of concern for preserving the length of the donor bile duct stump, it may increase the number of openings in the bile duct of the graft, increase the difficulty of recipient bile duct anastomosis, and increase the risk of postoperative bile leakage (12,13). Therefore, surgeons should accurately determine the appropriate biliary transection point to reduce the occurrence of biliary complications (113). Traditional living liver transplantation routinely uses preoperative MRCP combined with intraoperative cholangiography to accurately assess variations in the donor bile duct. Recently, ICG cholangiography under fluorescent laparoscopy has been widely used as a functional antegrade cholangiography method for laparoscopic donor hepatectomy. Owing to the characteristic ICG concentration in bile, fluorescent laparoscopy can be used to clearly observe the bifurcation point of the left and right hepatic ducts, thereby more accurately determining the biliary transection point in real-time (114,115).

Biliary stump management

In the management of biliary stumps, both clamping and suturing are viable methods (25). Although some researchers (70,116) have reported that suturing under laparoscopy increases the chances of bile leakage, for donors with shorter biliary stumps, forced clamping can increase the risk of postoperative biliary stricture; therefore, suturing should be used.

Recommendation 20: During biliary dissection, excessive dissection should be avoided, and energy instruments should be used cautiously to protect the blood supply around the bile duct (Evidence level: IV; Recommendation strength: Strong).

Recommendation 21: In the process of managing the biliary stump, both clamping and suturing are viable methods (Evidence level: IV; Recommendation strength: Strong).

Recommendation 22: During the evaluation of biliary *variation, MRCP should be performed preoperatively to assess the condition of the bile duct. Except for left lateral sectionectomy, intraoperative cholangiography or ICG cholangiography should be performed to determine the biliary transection point (Evidence level: IV; Recommendation strength: Weak).*

Indications and timing for conversion to open surgery in minimally invasive surgery

Ensuring donor safety is a primary task during minimally invasive surgeries for living liver transplant donors. Any event that may jeopardize donor safety or graft integrity should prompt rapid intraoperative conversion to open surgery. These include difficulties in controlling bleeding, the inability to accurately expose important anatomical structures, the inability to accurately identify variations in the bile duct or vascular anatomy, the occurrence of bile duct or vascular injury, and severe gas embolism. A study (117) involving 34 centers worldwide and 2,370 patients found that the intraoperative conversion rate reached 3.86–5.37%. Therefore, surgeons should rationally consider intraoperative conversion, and its occurrence should not represent surgical failure (118).

Recommendation 23: Any event that may jeopardize the donor's safety or graft integrity should prompt a rapid conversion to open surgery. These include difficulty in controlling bleeding, inability to accurately expose important anatomical structures and identify variations in the bile duct or vascular anatomy, occurrence of bile duct or vascular injury, and severe gas embolism. (Evidence level: IV; Recommendation strength: Strong).

Learning curve of minimally invasive surgery for living liver transplant donors

The implementation of minimally invasive surgery for living donor liver transplantation requires physicians with extensive experience in laparoscopic and open living donor hepatectomy (2,39,78). According to the literature (25,44,119), the incidence of postoperative complications in donors is significantly higher in the early stages of laparoscopic donor hepatectomy than in the later stages. Broering *et al.* demonstrated that the learning curve for pure laparoscopic donor left lateral sectionectomy was completed after 25 procedures (120). However, due to the deeper positioning, anatomical complexity, and larger graft weight of the right hemiliver than the left lateral sectionectomy, more cases need to be learned. Hong *et al.* (121) used the cumulative sum method to analyze the operation time of laparoscopic living donor right hepatectomy by the same surgeon and believed that the learning curve of this operation is 65–70 cases and that the formulation of standardized procedures and sharing of experience can shorten the learning curve. Medical institutions and physicians who have just started performing laparoscopic donor hepatectomy should choose donors with good anatomical structures (25,122). Before safely handling donors with more challenging anatomical variations, good anatomical structure can enable surgeons to accumulate experience and standardize techniques (123).

Currently, the application of robotic surgical systems in donor hepatectomy of living donor liver transplantation is relatively limited, and support from prospective clinical studies is lacking. Although its technical feasibility has been demonstrated, it has not been widely adopted in various transplant centers. Robots have multiple advantages over laparoscopy in minimally invasive liver surgery, making robotic living-donor hepatectomy an emerging research focus in liver transplantation. For institutions planning to perform robotic living-donor hepatectomy, having physicians with extensive experience in both open-living donor and robotic liver surgeries is essential. Additionally, establishing a dedicated robotic team, including the primary surgeon, assistants, and surgical nurses, can enhance donor safety and surgical efficiency and accelerate learning. Seeking collaborative teaching from experienced teams is beneficial, as this can significantly shorten the learning curve (30).

Recommendation 24: The implementation of minimally invasive surgery for living liver transplant donors requires physicians with extensive experience in minimally invasive and open living donor hepatectomy (Evidence level: V; Recommendation strength: Strong).

Recommendation 25: For transplant centers that lack experience in minimally invasive surgery for living liver transplant donors, starting with laparoscopic donor left lateral sectionectomy is recommended. With donor safety as the primary goal, a steady transition to laparoscopic donor hemihepatectomy surgery can be made (Evidence level: V; Recommendation strength: Strong).

Recommendation 26: Before mastering minimally invasive surgery for living liver transplant donors, it is advisable to avoid selecting donors with anatomical variations for surgery (Evidence level: III; Recommendation strength: Strong).

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Footnote

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