



Minimally-invasive donor hepatectomy at the dawn of a decade: can we pick up the pace?

Mark L. Sturdevant^{1,2}, Ahmed Zidan¹, Dieter Broering¹

¹Organ Transplant Center, King Faisal Specialist Hospital and Research Center, Riyadh, Saudi Arabia; ²Department of Surgery, Division of Transplant, University of Washington Medical Center, Seattle, WA, USA

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Correspondence to: Prof. Dieter Broering, MD, PhD, FEBS, FACS. Director of Organ Transplant Center, King Faisal Specialist Hospital and Research Center, MBC 96, P.O. Box 3354, Riyadh 11211, Saudi Arabia. Email: dbroering@kfshrc.edu.sa.

Abstract: Next year will mark two decades since the first minimally-invasive donor hepatectomy (MIDH) was performed in Paris to facilitate an adult-to-child live donor liver transplant (LDLT). Despite improvements and widespread proliferation of LDLT throughout the world, a concomitant broader application of the MIDH technique has not been wholly realized due to concerns over donor safety and the technical difficulties inherent to MIDH. On the contrary, during the same time period, minimally-invasive liver surgery (MILS) rapidly evolved into a standard approach for many benign and malignant forms of liver disease. To support this growth, numerous novel technologies such as advanced laparoscopy and robotic surgical systems, three-dimensional (3D) flexible videoscopes, real-time near-infrared fluorescence cholangiography with indocyanine green (ICG), and a variety of thermal energy devices and endovascular staplers have evolved and matured in the setting of MILS. A handful of select, high-volume liver transplant centers have incorporated these MILS advancements into their established segmental liver surgery and LDLT programs in order to develop the requisite technical sophistication to execute MIDH in an impactful manner. Two techniques, pure laparoscopic donor hepatectomy (PLDH) and robotic donor hepatectomy (DH), have emerged as the dominant modalities in MIDH surgery with each having their proponents and detractors. A few centers in Asia, France, the United States, and Saudi Arabia have recently reported series of sufficient volume and nuance to be instructive for the field in general. The intent of this review is to describe the experience to date in MIDH with a particular focus on lessons learned at these pioneering institutions who navigated through the learning curves in these demanding technical endeavors. The tricks, observations, and recommendations gleaned from this article should serve as a vital resource for those motivated surgeons embarking upon the challenging but rewarding field of MIDH surgery.

Keywords: Donor hepatectomy (DH); robotic donor hepatectomy (robotic DH); pure laparoscopic donor hepatectomy (PLDH); living donor liver transplantation (LDLT); minimally-invasive donor hepatectomy (MIDH)

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Introduction

The marked imbalance between the escalating need for liver transplantation (LT) and the plateaued availability of quality deceased donor organs remains as the primary and continual stimulus for living donor liver transplantation

(LDLT). In many Asian and Middle Eastern countries, cultural issues further compound the challenge and render LDLT as the only viable option for those with advanced and life-threatening liver disease. A commensurate expansion of LDLT to offset this disparity is yet to be actualized in

most countries due to concerns related to the potential negative impact living donor hepatectomy (DH) may have on donor safety and quality of life. Despite accumulating experience and technical refinements, international studies suggest that DH carries a 0.2–0.6% mortality rate with an accompanying 20–40% overall complication rate (1,2). Furthermore, the majority of the severe complications (Clavien-Dindo ≥ 3) are related not to postoperative hepatic insufficiency but instead due to the technical complications of this demanding procedure, which can be hampered by suboptimal visualization, the inherent need for an upper abdominal wall incision, and imperfect modalities to avoid and control bleeding and bile leaks.

Contemporaneous with the establishment of open DH surgery in the 1990s and early 2000s, minimally-invasive liver surgery (MILS) was adopted and rapidly evolved in many parts of the world. In the 2008 Louisville Statement, an international expert panel declared it to be standard practice for minor and some major resections in selected patients (3). This reflected a recognition that reduced postoperative morbidity, speedier recovery, and pronounced aesthetic improvements had been produced at high-volume and specialized centers utilizing MILS. The subsequent application of this innovative approach to living DH has been deliberate and began in Paris with Cherqui *et al.*'s 2002 report on a laparoscopic left lateral sectionectomy for donation (4) which was followed by a 2005 report from Northwestern wherein Koffron described how laparoscopic-assistance was utilized to perform a right DH (5). In the last 15 years, minimally-invasive donor hepatectomy (MIDH) has evolved into a well-established clinical endeavor with the clear intent of mitigating the short- and long-term complications that plague living liver donors undergoing conventional open DH (6). The subsequent monograph will detail the requisite elements that were combined to develop the current state of MIDH which presently has proponents developing the field through pure laparoscopic or robotic-assistance means. More importantly, this review should serve as a platform for the dissemination of ideas and experience, some painstakingly developed over many years, which will enable MIDH to be more broadly implemented into mainstream liver donor surgery.

Laparoscopic-assisted donor hepatectomy (LADH)

Subsequent to the initial series from Paris and Chicago (7,8), which did show that LADH afforded donors the

advantages of less pain and wound-related complications with comparable operative times, a number of institutions in the East became early adopters of the practice. Innovators in several Japanese centers and India applied their advanced laparoscopic skills to perform all but the parenchymal transection in their initial LADH experience thus employing the so-called “hybrid” or LADH technique of MIDH. These early series in Japan were primarily comprised of left-sided procurements include the challenging left lobe with caudate graft type (9-11).

The most impactful advancements in LADH came from the stepwise approach which was implemented at Seoul National University in 2007. Minimally-invasive donor surgery initially consisted of a mini-laparotomy (i.e., 12–18 cm open incision) technique and to a lesser extent at least initially with a hybrid (i.e., hand-assistance) LADH approach. For several years, LADH accounted for well under 10% of their total DH, but a sharp upsurge in activity occurred in 2015 when over 25% of donors underwent LADH. This significant change was primarily attributed to the debut of three-dimensional (3D) flexible laparoscopy which provided unprecedented optical advantages (12,13). Likewise, the group in Morioka began employing their well-described laparoscopic-assisted resectional technique with hanging maneuver in their living donor hepatectomies in 2007 (10). After a 5-year experience encompassing 40 LADH cases in a relatively balanced group of right and left lobe donors, they opted to move on to a purely laparoscopic technique citing the safety advantages afforded to them by the 3D flexible laparoscope and parenchymal transection under both pneumoperitoneum and magnified optics.

In April of 2018, encouraged by favorable results in our large ($n > 100$), single center experience in pure laparoscopic donor left lateral sectionectomy (14), we initiated a MIDH program for hemi-hepatectomy donors. We initially implemented a LADH technique with the following tenets: (I) trocar placement was predicated on an anticipation of an upper midline incision for final parenchymal transection and graft extraction, (II) 3D video-laparoscopy was utilized to provide optimal visualization to facilitate right lobe mobilization and identification of vascular structures during hilar and parenchymal dissection, (III) direct hepatic vein control was performed with the aid of the Challenger[®] pneumatic multi-fire clip applier, (IV) hilar dissection was performed as we do in open donors, (V) indocyanine green (ICG) fluorescence was used to optimize the transection line along Cantlie's line, (VI) parenchymal transection was performed with CUSA and under laparoscopic-assistance

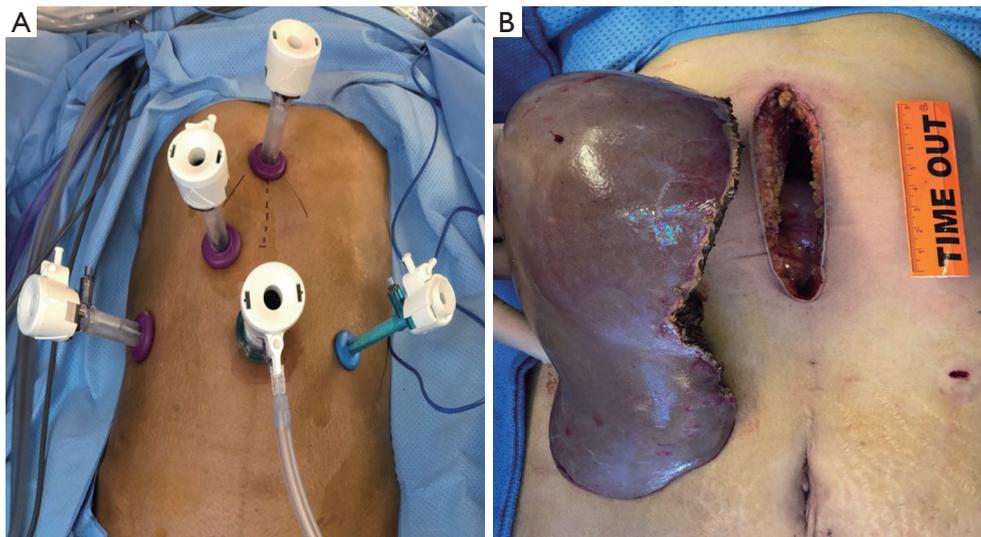


Figure 1 Trocar placement for laparoscopic right hepatectomy. (A) Trocar placement for right LADH; (B) 10-cm extraction site for a 777-gram right hepatic lobe. LADH, laparoscopic-assisted donor hepatectomy.

for a variable amount of time depending on liver thickness, time under anesthesia, and general progression of the procedure, and (VII) in order to transition to the open phase of the DH, we connected the two upper midline trocar sites, entered the abdomen, established the hanging maneuver and completed the remainder of the hepatectomy as we do in our open technique (see *Figure 1*).

Over an 8-month period, we performed twenty-six right lobe LADHs with an average graft size of 704 [538–1,012] gm in a donor cohort with an average BMI of 23.6. The operative time was well over 7 hours; the estimated blood loss was 321 [200–500] mL and no blood transfusions were required. The safety profile of the LADH technique was promising in that there were no serious complications (Clavien-Dindo ≥ 3) and there was an overall complication rate of 11.5% which did include a single self-limited bile leak. Instructive impressions gleaned from this preliminary experience included the following: (I) LADH in hemihepatectomy donors had a comparable safety profile to our open cohort, (II) the cosmetic result was noticeably superior to the open technique but only marginally so when compared to our DH by way of midline mini-laparotomy (see *Figure 2*), and (III) opioid-based analgesia was still required due to the upper midline incisional location. Like our colleagues to the East, we share the perception that LADH is not a destination procedure as it inadequately confers to the donor the full measure of benefit that is inherent to MILS. We do feel that it should retain its

important place as the final maturation phase before proceeding to true MIDH.

Pure laparoscopic donor hepatectomy (PLDH)

The precise resection of a left lateral section or hemi-liver with a preserved vasculobiliary pedicle (i.e., transplantable graft) through a purely laparoscopic technique is a formidable task. Considering the ramifications that it carries for both the living donor and recipient, it comes as no surprise that it is considered the apex operation of contemporary liver surgery. The level of technical sophistication sufficient to perform and advance PLDH surgery was acquired by combining the following requisite elements which were developed in several sub-disciplines of hepatic surgery: (I) a keen knowledge of segmental liver anatomy through vast experience in open DH, LDLT, and *in situ* liver splitting, (II) mastery of laparoscopic liver surgery through years and decades of practice, (III) in hemihepatectomy PLDH, laparoscopic-assistance techniques have been influential in bridging the learning curve, and (IV) the ability to utilize advancing technology (i.e., 3D flexible laparoscope, ICG) to produce safer results (see *Figure 3*).

Pure laparoscopic left lateral sectionectomy (PL-LLS)

Cherqui and Soubrane's index cases of PL-LLS established the field and are now part of the mounting number of

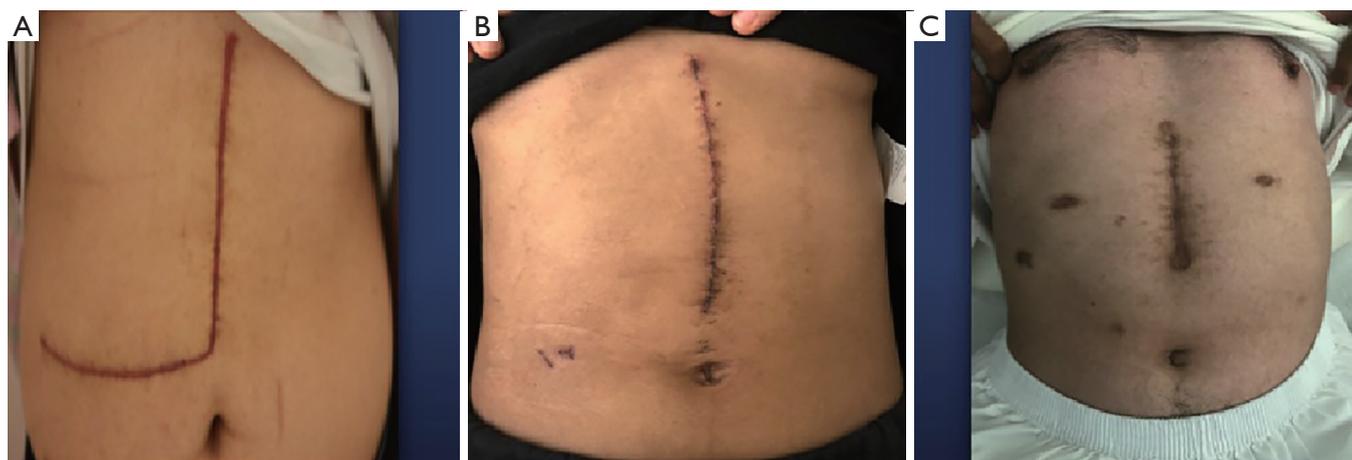


Figure 2 Scar formation after donor right hepatectomy via (A) open approach, (B) mini-laparotomy, (C) laparoscopic-assistance.

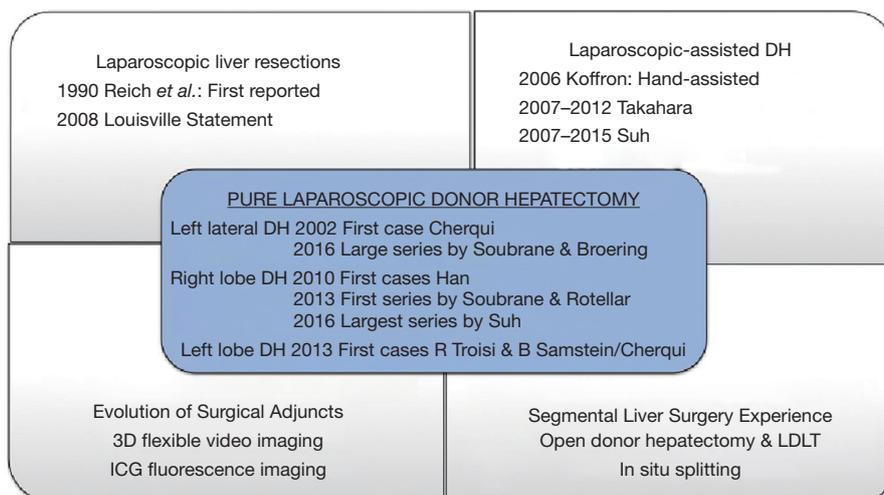


Figure 3 Requisite elements in the development of PLDH. PLDH, pure laparoscopic donor hepatectomy; LDLT, living donor liver transplantation.

large clinical series (see *Figure 3*) that displays the slow but perceptible dissemination of the technique. This accurately reflects the fact that the institution must have a breadth of experience in both advanced laparoscopy and segmental liver surgery to support the endeavor in such a high-profile patient population. In May of 2013, we addressed this vexing problem by implementing a proctorship program wherein an advanced laparoscopic liver surgeon transiently joined our team to provide real-time feedback to our lead surgeon during the inceptive phase of our MIDH program. This facilitated a safe navigation through the so-called learning curve portion of our experience in PL-LLS, which

based on our recent retrospective analysis, consisted of the first 25 cases. Our standardized technique, described in detail in two previous publications (14,15), was executed in over 120 PL-LLS cases before transitioning to a robotic system in 2018. For completeness sake, we want to highlight the following technical aspects of the PLDH technique as performed at the King Faisal Specialist Hospital:

- ❖ Donor position is split leg with a 20°–30° tilt.
- ❖ Five trocars (5/10/12/12/5 mm) are inserted in the upper abdominal quadrants and a 3D flexible laparoscope is utilized. Pneumoperitoneum is maintained at 10–12 mmHg.

Table 1 Pure laparoscopic donor left lateral sectionectomy

Institution	N	Outcomes	Complications	Lessons learned
King Faisal Hospital, 2013–May 2017	72	OR time: 293 m; conversion: 4.2%	G1–2: 2.8%; G3: 1.4%	Learning curve =25 cases. 50 most recent cases: 1 conversion, no complications
Paris (Cochin & St. Antoine), 2001–2014	63	OR time: 271 m; conversion: 7.9%	G1–2: 17.4%	1 st case worldwide 2001. Optimized outcomes by consolidating cases to 2 surgeons
Asan MC, 2008–October 2009	11	OR time: 330 m	G1: 9%	Shorter LOS & time to oral diet. Comparable outcomes vs. open DH
International* multicenter, 2001–2014	124	OR time: 308 m; conversion: 3.2%	Overall =17%; G3 =4.8% with 4 reoperations	Lap donor LLS = a new standard practice for DH. Less complications vs. lap nephrectomy

*, Of 124 donors, Paris =64, Seoul =25, New York =16, Lyon =13, Ghent =6. Of note, there were no donor mortalities at any institution. Single-centers reported equivalent LDLT for recipients of PLDH-LLS grafts and the 90-day recipient mortality in the international study was 3%. LDLT, living donor liver transplantation; PLDH, pure laparoscopic donor hepatectomy; LLS, left lateral sectionectomy.

- ❖ The falciform and the left triangular ligaments are divided with Ligasure (Medtronic, Minneapolis, MN, USA). The Arantius ligament is divided in order to identify the location of the left hepatic vein, however, overzealous dissection of the left hepatic vein is not advisable at this juncture.
- ❖ The hepatic hilum is dissected with a combination of blunt and hook electrodissection and the arterial supply to the left liver (both left lateral artery and artery to segment 4) is identified. We also encircle the left portal vein down to the caudate branches.
- ❖ The parenchyma is divided using the ultrasonic aspirator similar to open surgery. Early parenchymal transection can facilitate the isolation and division of segment 4 portal vein branches. During parenchyma transection, vessels were sealed or clipped using titanium or Hem-o-lock clips (Teleflex, Chicago, IL, USA).
- ❖ The hilar plate is typically addressed by securing it with two titanium clips prior to transection but suture ligation is also utilized if needed.
- ❖ After dissection of the portal branches to the caudate lobe, a “tunnel” is created between the left side of the caudate lobe and the cutting line to complete parenchymal division until the confluence of the left to the middle hepatic vein (MHV).
- ❖ At the end of parenchyma transection, a Pfannenstiel incision is made and serves as the extraction site by allowing for the introduction of a 15 mm trocar (Endocatch 2 bag) for graft extraction.
- ❖ The left lateral lobe was detached according to these steps:

- ♦ Cut the hepatic artery after securing the donor side with 2 Hem-o-lock clips.
- ♦ Cut the left portal vein after securing it with 1 Endo TA 30-mm stapler.
- ♦ Secure and divide the left hepatic vein at its confluence with the MHV with an Endo GIA™ 60 mm.
- ❖ The LLS graft is extracted through the Pfannenstiel incision.

In 2018, we compared 72 consecutive donors who underwent PL-LLS and compared them using propensity score matching with a historical cohort of open donors (14). As one might expect for an innovative laparoscopic procedure, the mean operative and warm ischemia times of 244 and 5 minutes were significantly longer compared to those undergoing open surgery but neither appeared to be clinically important. The instructive lessons from this large series include: (I) the laparoscopic technique is safer than the open procedure as the overall complication rate was just over 4% as compared to 29% in the open group, (II) a single bile leak (Clavien-Dindo grade 3) did occur and was managed with an ERCP, and (III) the recipient outcomes were equivalent.

Similar findings in leading centers in Asia, Europe, and the United States (see *Table 1*) has led to an international consensus recommendation declaring that the laparoscopic approach should be viewed as the new standard of practice (16). Based on our favorable results, we echo this recommendation. With experience, we also feel that the PL-LLS can be applied to nearly all donors regardless of anatomic variations such as double hepatic arteries to the LLS or segment 4 hepatic venous drainage to the left

Table 2 Pure laparoscopic donor hemi-hepatectomy (PLDHH)

Institution	N	Outcomes	Complications	Lessons learned
Seoul National Univ., Nov. 2015–June 2017	115 All Rt	OR time: 322 m; WIT: 11 m	≥ G3: 2.6%; no transfusions	Most important = open DH experience. Flex 3D and ICG helpful
Samsung University, May 2013–Feb. 2015	54: 51 Rt, 3 Lt	OR time: 436 m; WIT: 6 m; conversion: 7.4%	Overall 33%; ≥ G3: 16.7%; no transfusions	Donor selection important: 45% complication rate with PV or bile duct variants
NY Presby/Columbia, 2012–Oct. 2017	51: 12 Rt, 8 Lt, 31 LLS	OR time: 429 m; conversion: 10%	≥ G3: 12%; transfusion 4%; bile leak 4%	Learning curve ~45–60 cases. In last 3 yrs, PLDH used in 45% of all donors
Morioka Japan, 2012–2014	14: 9 Lt, 5 Rt	OR time: 455 m; WIT: 9 m; conversion: 7%	≥ G3: 21% (3 bile leaks); no transfusions	Clips are insufficient for bile duct closure. Optimal pneumo =12 mmHg

Of note, there were no donor mortalities at any institution and the LDLT outcomes were equivalent using PLDH grafts. LDLT, living donor liver transplantation; PLDH, pure laparoscopic donor hepatectomy.

hepatic vein. What is yet to be answered, pertains to the extent to which centers who are only performing a handful of these procedures annually can combine the necessary elements to produce proficiency in this demanding technique. In these centers, the importance of collaboration and proctorship to enhance and augment the limited experience in laparoscopic DH cannot be overstated and may serve as the most plausible solution to this quandary.

Pure laparoscopic donor hemi-hepatectomy (PLDHH)

Eight years passed between Cherqui's laparoscopic DH and proof of concept in right lobe PLDH by Han in Korea 2010 (17) and Soubrane a few years later in 2013. That same year in Ghent, Troisi reported on four living donors who underwent left lobe PLDH (18). Concurrent with these technical achievements was the continued proliferation of LDLT in Asia and in particularly Korea, a country also replete with high volume centers in the practice of MILS. Three of the leading centers in Seoul now make up the majority of PLDHH activity worldwide. To date there are only four centers with publications reporting on 10 or more PLDHH donors (19–24) and their surgical outcomes and safety profile are reviewed in *Table 2*.

Detailed donor selection approaches and technical descriptions of their respective operations have been previously described by several groups (12,19–23). In a recent survey study of nine PLDHH international experts (25), surgeons opined on the following aspects of PLDHH:

- ❖ Donor selection criteria: (I) unanimously agreed that they apply stricter, albeit ill-defined criteria to these donors, (II) only one routinely performs PLDHH in

the setting of a biliary trifurcation (III) 3/9 surgeons do not offer PLDHH when the recipient has a MELD >35, and (IV) 3/9 surgeons require a larger future liver remnant in PLDHH donors.

- ❖ Technical details: (I) 5/9 surgeons use 3D videoscopy while 4/9 use a flexible laparoscope, (II) 4/9 use intraoperative cholangiogram (III) 6/9 surgeons prefer to suture the remnant bile duct stump and (IV) 5/9 employ endovascular staplers are to handle the portal vein and it is unanimously endorsed as the preferred technique to manage the hepatic vein.
- ❖ Future role of PLDHH: only one of nine experts felt that PLDHH should not become the standard at experienced centers but no one confidently felt that it could be disseminated universally.

The results to date from the leading centers in the field are encouraging. Most importantly, no mortalities, post donation liver failure, or major near-miss events have been reported in the PLDHH literature. Bile leaks and strictures are clearly the most common serious complication reported (see *Table 2*) and continued efforts to minimize this potentially life-threatening problem centers on (I) optimal donor selection (II) use of ICG fluorescence or intraoperative cholangiography (IOC), and (III) maximizing surgical team experience. All of the pioneering groups in PLDHH grappled with biliary issues including higher rates of supernumerary bile ducts after right lobe PLDHH, bile leaks especially in those with atypical anatomy (23), and even biliary stricture most likely due to overzealous dissection near the remnant duct. As exemplified by the group at Seoul National University, who estimate that the

learning curve subsides after 60 cases, serious complications can become exceedingly uncommon (24).

Robotic living donor hepatectomy (RLDH)

Sound innovation must be principled. In living donor surgery this clearly means that any advancement must preserve the time-tested surgical tenets that have been developed over the last three decades. Proponents of the robotic surgical system argue that it is the best contemporary modality of MIDH because it allows the surgeon to most closely emulate the steps learned in open surgery. Its effectiveness stems from the following attributes:

- ❖ Inflicts markedly less abdominal wall trauma without any need for upper abdominal wall incisions.
- ❖ Steady, magnified and high-resolution 3D visualization which facilitates the identification of potential bleeding sources and allows for precise dissection of vasculobiliary structures. The presence of depth perception eases the complexity of intracorporeal suturing.
- ❖ The parenchymal transection is simplified by the enhanced optics, pneumoperitoneum, and deft suturing capabilities when energy sources and clipping are ineffective.
- ❖ Superior dexterity and instrument articulation sans the tremor which allows for meticulous short hepatic vein dissection and isolation of the hilar vasculature.
- ❖ Surgical adjuncts such as real-time ICG (Firefly Technology) to aid with delineation of biliary anatomy.

These theoretical advantages were first employed in 2011 at the University of Illinois-Chicago when Giulianotti completed the first right lobe RLDH (26) after developing proficiency by completing over 70 robotic hepatectomies for disease (27). The combination of cost and novelty has since hindered its widespread application in hepatic surgery for living donors and only a few centers worldwide now have substantive experience with it. Until recently, the only sizeable published contribution was by the group at National Taiwan University in Taipei who initiated their RLDH program in 2013 and published a small but instructive series of 13 right-sided RLDHs in 2016 (28,29).

Convinced of its merits and following a collaborative proctorship with the team from Taipei, we introduced RLDH into our program at Riyadh in November of 2018. The following prerequisites were in place at our institution

prior to initiating this program, all of which we feel were instrumental in its success to date:

- ❖ Extensive experience in open DH and PL-LLS. Our console surgeon (DB) had performed >500 open DH and >100 PL-donor left lateral sectionectomies prior to initiating the robotic program.
- ❖ Console training in minor hepatobiliary cases such as laparoscopic cholecystectomy. Our team was devoid of extensive robotic hepatectomy experience and the console experience was limited to training and in these minor cases. This suggests that it may be the more applicable form of MIDH (i.e., flatter learning curve) to surgeons without extensive skills in MILS.
- ❖ We established a consistent operative team with no personnel deviation in regard to the bedside surgeon and scrub technicians. This was imperative to maximize safety, efficiency, and rapid learning in order to mitigate the learning curve.
- ❖ Donor selection: We did not deviate from our liberal selection criteria for left lateral section and left lobe grafts. However, in the introductory phase of our robotic experience we did select grafts with conventional anatomy and of modest size (<800 gm right lobes). After 25–30 cases, we gravitated to a relatively forgiving selection criteria and did not exclude donors with trifurcated biliary anatomy. This rapid acceptance of the technique for nearly all donors is reflected by the fact that only six right lobe donors were procured through an open approach during this 18-month experience.
- ❖ The collaborative proctorship was comprehensive and was initiated with a visit by our lead surgeon to the group in Taipei. After agreeing on donor selection, we then sought hands-on advice relating to donor position, trocar placement, docking, and utilized a double console approach to facilitate real-time learning.

The right lobe RLDH at the King Faisal Specialist Hospital & Research Center

- ❖ Surgical system: Da Vinci Xi System (Intuitive Surgical Inc.).
- ❖ Donor position: “French”, 20- to 30-degree reverse Trendelenburg position with the right shoulder up slightly and the assistant surgeon between the legs.
- ❖ Trocar placement: The assistant port (12-mm balloon trocar; Applied Medical, USA) is placed transumbilically

under direct vision, whereas the four other 8-mm robotic trocars were placed at a distance of 8 cm each on the right and left flank and arranged in the classical “smiling” line (see *Figure 4*).

- ❖ Initial steps: the liver is evaluated for quality and if favorable the operation commences with hook



Figure 4 Trocar placement for all robotic DH cases. DH, donor hepatectomy.

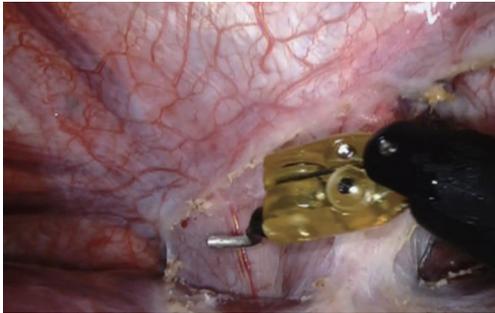


Figure 5 Cautery transection of the coronary ligament anterior to the IVC. IVC, inferior vena cava.

electrocautery transection of the falciform ligament down to the hepatic vein level (see *Figure 5*). Gallbladder traction (to the left) by a grasper from the umbilical port in concert traction from with the robotic arm #4 (pro grasper) exposes the coronary ligament which is divided with a monopolar hook (see *Figure 6A*). Stepwise mobilization brings the inferior vena cava (IVC) into view.

- ❖ Clockwise dissection of the retrohepatic IVC is performed using two robotic bipolar Maryland dissector. Retrohepatic veins up to a diameter of 2 mm were coagulated by bipolar coagulation and 3–5 mm veins were transected between titanium clips (see *Figure 6B*) or with suture ligation (5/0 absorbable monofilament suture). Retrohepatic veins larger than 5 mm were clipped on the graft side with titanium clips (Challenger clips; Aesculap, Germany) and sutured toward the cava. Once the caval ligament is divided, the right hepatic vein (RHV) is isolated.
- ❖ In order to facilitate a hanging maneuver, a tunnel is fashioned in the avascular space between the RHV and the MHV. A 10-Fr silicone Foley catheter is placed longitudinally just anterior to the IVC and once its tip traverses the opening between the RHV/MHV, it is Hem-o-locked to set it into place (see *Figure 7*).
- ❖ Hilar dissection: the liver is placed into the anatomic position and a cholecystectomy is performed. The ligated cystic duct is retracted cephalad by the bedside surgeon which exposes the right hepatic artery (RHA) which is readily isolated and dissected. The articulating prowess of the robotic dissectors are used to isolate and loop the right portal vein (RPV). All of this dissection

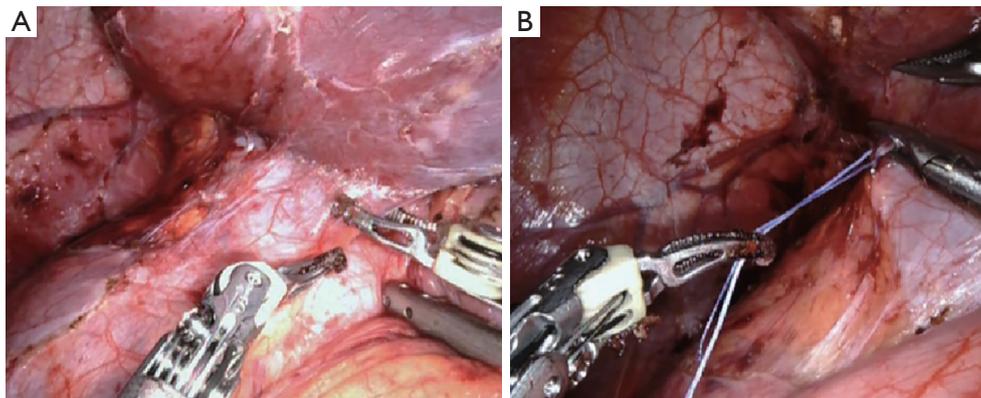


Figure 6 Robotic right lobe mobilization. (A) Mobilization of the right hepatic lobe and (B) direct hepatic veins transection.

remains to the right of the bile duct.

- ❖ Parenchymal demarcation: laparoscopic bulldogs, via the umbilical port are placed on the RPV and RHA (see *Figure 8A*) and followed by intravenous administration of 0.5 mg/Kg of ICG (Verdye; Diagnostic Green, Germany). Near-infrared fluorescence (Firefly; Intuitive Surgical) is activated to interrogate Cantlie's line which is marked via hook electrocautery (see *Figure 8B*). The bulldogs are removed and two traction sutures (2-0 Prolene) are secured into the liver on either side of the transection line and subsequently fixed outside the abdomen by clamps.
- ❖ Parenchymal transection: the robotic Harmonic scalpel (Ethicon) is used to divide the parenchyma (see *Figure 9*). Small crossing veins are handled with thermal devices while larger (≥ 8 mm) veins are controlled with titanium clips, 5-0 suture ligature sutures, or an endovascular stapler (Covidien Endo GIA 30 mm; Medtronic, MA, USA).

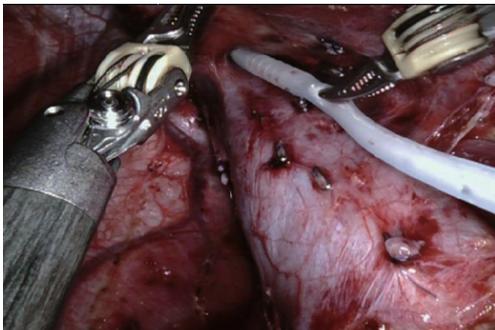


Figure 7 Preparing for the hanging maneuver.

- ❖ Right hilar plate transection: after completion of 80% of the parenchymal transection, the right hilar plate is brought into view and real-time ICG (Firefly) is activated in order to identify the ideal site for right hilar plate transection (see *Figure 10A*). After initial opening of the duct, duct exploration with a lacrimal probe (Bowman lacrimal probe AL1330; MicroSurgical Technology) documents the main donor bile duct bifurcation and gauges the length of the right bile duct stump (see *Figure 10B*). A right hepatic duct stump of 2 mm is mandatory on the donor side. Closure of the right bile duct(s) stump(s) is done using interrupted 6/0 polydioxanone suture (PDS) stitches.
- ❖ The 10-Fr silicone Foley catheter is superficialized by passing it between the right hilum and the parenchyma and grasped with the arm 4 pro grasper thus establishing the hanging maneuver (see *Figure 11*). The parenchymal transection is readily completed with the performed with the Harmonic scalpel (Ethicon).
- ❖ Create the extraction site: a Pfannenstiel incision (8–11 cm) is made approximately 3 cm superior to the pubic bone and a 15-mm trocar with a 15-mm Endo Catch II bag (Medtronic) is placed into the abdomen. The right lobe is partially inserted into the Endo catch pouch.
- ❖ Vascular control and transection sequence:
 - ♦ The RHA is doubly clipped (Weck Hem-o-lok; Teleflex, Morrisville, NC, USA) and transected.
 - ♦ The RPV is secured and transected with a 35-mm articulating power echelon vascular stapler (Johnson & Johnson, USA). Always leave enough donor RPV to minimize the incidence of portal vein stenosis.

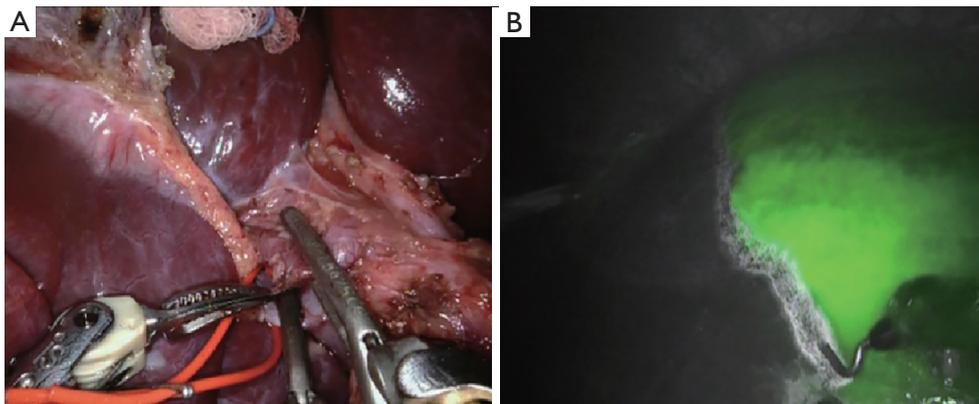


Figure 8 Identification of demarcation line. (A) The RHA and RPV are transiently clamped and (B) real-time ICG infusion provides confirmation of the demarcation line. RHA, right hepatic artery; RPV, right portal vein; ICG, indocyanine green.

- ♦ The RHV is secured and transected (see *Figure 12*) with 60-mm Endo GIA curved tip tanned stapler (Covidien Tri-Staple Endo GIA).
- ❖ Extraction: the graft is placed with care into the endocatch bag (see *Figure 13*) and extracted through the Pfannestiel incision and immediately flushed on the back table with histidine tryptophan ketoglutarate (HTK) solution (Custodiol, Franz Koehler Chemie, Germany).
- ❖ Final steps: pneumoperitoneum is reestablished to exclude bleeding followed by peritoneal closure and fascial closure at the extraction site. The entire surgical dissection field is surveilled for bleeding or bile leak and the cut surface is covered with Tachosil. One drain is placed on the cut surface prior to trocar removal and skin closure. As in open DH surgery, the falciform is

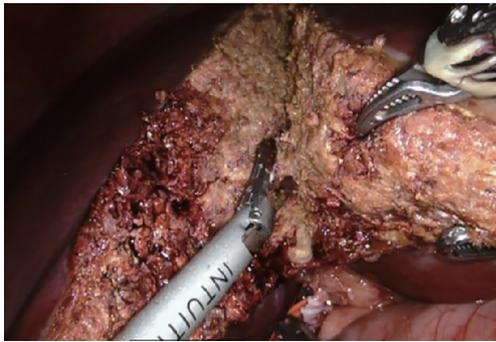


Figure 9 Harmonic parenchymal transection without pringle.

reapproximated to avoid torsion (see *Figure 14*).

Caveats in the left lobe RLDH

- ❖ Identical donor positioning and trocar placement.
- ❖ Liver mobilization focuses on exposing the left/MHV by dividing the left side of coronary and triangular ligaments. The left lateral segment is retracted upward and medially by the fourth robotic arm and the gastrohepatic ligament up to the Arantius ligament is divided.
- ❖ Hilar dissection/parenchymal: the left hepatic artery and left portal vein are isolated with the same technical principles as previously stated, and this is followed by identical steps in Cantlie line demarcation.
- ❖ Division of the left of common bile duct is performed with Firefly mode assistance.

Caveats in the left lateral section RLDH

- ❖ Same principles as right and left lobe donor hepatectomies.
- ❖ The trans umbilical approach is preferred in our center with placing the cutting line just medial to falciform ligament. This innovation by the Hamburg group serves to minimize segment IV bile duct and artery injuries.
- ❖ The hilar vascular dissection is facilitated by firm traction and the left hepatic vein is endostapled from robotic arm #1 (see *Figure 15A,B,C*).

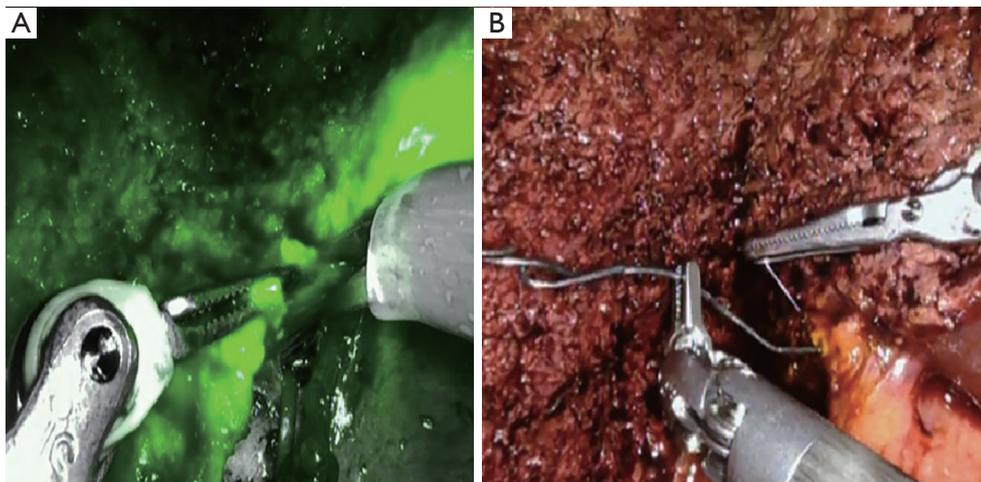


Figure 10 Cutting the hilar plate and bile duct probing. (A) Sharp transection of the right hilar plate with assistance from ICG, (B) probing of the remnant right hepatic duct stump to confirm the location of the transection. ICG, indocyanine green.



Figure 11 The robotic hanging maneuver.



Figure 12 Endovascular stapler control of the RHV. RHV, right hepatic vein.



Figure 13 Right hepatic lobe just before extraction.

Robotic DH: our take after 175 cases in 18 months

As demonstrated in *Table 3*, complete commitment to the robotic modality was undertaken at our institution with permissive inclusion criteria as reflected by the fact that only six open donor hepatectomies (all right lobe) were performed during this 18-month period. Immersion into the technique allowed us to rapidly navigate through the learning curve as we gained a concentrated experience in RLDH for all three conventional donor graft types.

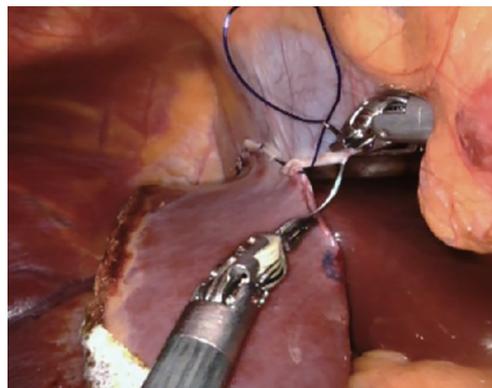


Figure 14 Robotic suturing to reapproximate the falciform ligament to avoid torsion.

First and foremost, we immediately recognized a sense of amplified donor safety which was produced by the combination of the aforementioned enhanced optics and the superior dexterity and instrument articulation. Quite simply, it allowed us to emulate the open donor operation but in a much better way—and, everyone in the room could actually see! The ability to readily recognize vascular structures both in the hilar dissection and parenchymal transection resulted in clean surgical dissections (aided by pneumoperitoneum as well). No conversions to open surgery were prompted by bleeding. Efficiency developed, especially with the right lobe donors, after we developed a semblance of mastery in the following technical maneuvers:

- ❖ Right lobe retraction/mobilization: the bedside and console surgeon must work in concert to adequately and atraumatically retract the bulky right lobe medially in order to facilitate proper exposure.
- ❖ Utilizing the harmonic scalpel for parenchymal dissection is not a widespread practice (we used CUSA for open and laparoscopic DH) but ultimately, we found it be quite effective especially when it can be supported by reliable clip placement and endovascular stapling for larger veins. Despite these advanced technologies, the ability to execute a well-placed stitch is imperative and must remain part of the surgeon's armamentarium to produce perfect surgery. There is no debate that the robotic surgical platform is superior to all other modes of MIDH in this regard.
- ❖ Accurate delineation of the biliary anatomy is accomplished by combining vast experience from open hepatectomy with the superior visualization

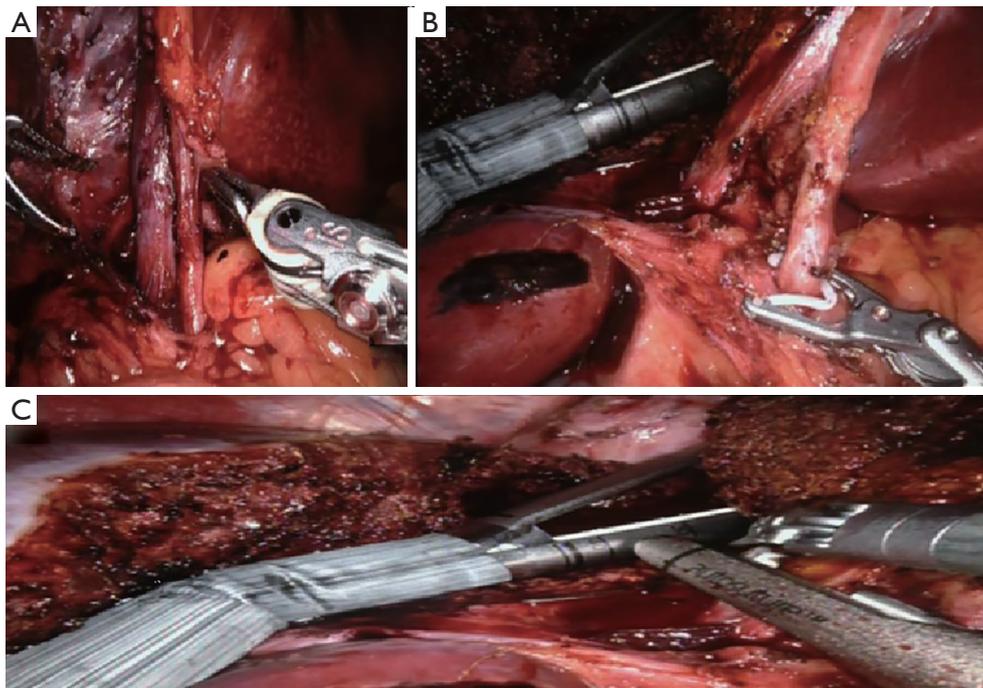


Figure 15 Stappling of inflow and outflow structures. (A) Dissection of left hepatic artery and left portal vein, (B) Hem-o-lok clipping of the left hepatic artery and (C) endovascular stapling of left hepatic vein.

Table 3 Robotic living donor hepatectomy (RLDH)

Institution	N	Outcomes	Complications	Lessons learned
National Taiwan Univ., May 2013–August 2015	13	OR time: 590; WIT: 9.5 m; no conversions	No G1/2; \geq G3 =7.7%; no transfusions	First series of RLDH, earlier return to work. Equivalent recipient outcomes despite WIT
King Faisal, Nov. 2018– May 2020	175: Rt 80, Lt 34, LLS 61	OR time: 424 m; WIT: 7.8 m; conversion: 1.1%; LOS: 4 days	Overall 6.8% all G1/2; bile leak 1.7%	Proctorship is useful. Equivalent bile duct #. Equivalent recipient outcomes
Yonsei Univ., April 2016– Sept. 2017	22	OR time: 555 m	Overall 18.2%; no transfusions	Feasible with longer OR times vs. open and no difference in complication rate
Illinois-Chicago, 2011	1	OR time: 480 m	G3: late portal vein stenosis	RLDH is feasible. Donor follow up is imperative

Of note, there were no donor mortalities at any institution. The National Taiwan and King Faisal groups both reported equivalent LDLT recipient outcomes using RLDH grafts. LDLT, living donor liver transplantation.

provided by the robotic system. We also reproduce our practice of biliary probing (after an initial small cut) to confirm our position within the biliary tree. The ICG (Firefly system), may clarify the anatomy akin to a conventional cholangiogram, but the results are far from uniform, so we caution against an overreliance on this emerging technology.

❖ Precise bile duct transection and stump closure is no longer a significant concern after developing proficiency in fine robotic suturing. We fully endorse the sentiments conveyed by Wakabayashi and colleagues in 2015 when they expressed a distrust in the reliability of remnant duct closure with clips. We agree with this skepticism precisely

because it deviates from the principles of open DH surgery. Instead, we utilize the robotic system to fully reproduce the open technique in regard to bile duct management and all ducts are closed with interrupted fine suture. Our negligible bile leak rate of just over 1% is a testament to this approach.

The overall complication rate of just under 7% (none \geq grade 3), 4 days length of stay, and absence of blood product transfusion in 175 RLDHs (unpublished) are almost predictable outcomes with the recognition that a conventional DH operation can be truly recreated in the enhanced environment of a robotic system platform (i.e., better optics, pneumoperitoneum, deft suturing, atraumatic access to the liver). We also are in agreement with the group from Taipei, that the learning curve of robotic major hepatectomy surgery may be a fraction of that noted in the laparoscopic technique (30,31). Practically speaking, an extensive background and experience in laparoscopic resection techniques may not be an absolute prerequisite to initiate a robotic DH program provided that basic minimally-invasive skills are present along with extensive proficiency in DH techniques. The development of the necessary robotic skills is required and should initially be performed in less strenuous and impactful operations.

The most poignant limitations of robotic DH are the absences of intraoperative cholangiogram and conventional (i.e., CUSA) hepatic transection modalities, both of which are heavily utilized at most centers during open DH. However, as stated before, the attributes of the robotic system platform make these challenges surmountable provided that the surgical team has a sufficient depth of experience in DH. Future iterations of the robotic system may introduce technical solutions to these issues that may be vexing to the novice robotic surgeon.

The path forward in MIDH

Three decades of work and progress in MILS, DH technique, and LDLT have now merged in such a way that a paradigm shift in living donor surgery is materializing in the form of MIDH. The impact of MIDH surgery is not limited to simply completing the operation with smaller, better-positioned, or more aesthetically pleasing incisions. Instead, the journey's end for MIHD will only reach its true potential when both the innovations and innovators synergistically join to in making living donation truly safer. The two most promising MIHD modalities, pure laparoscopy and robotic-assistance, have their respective

proponents and detractors but ultimately both approaches may find their niche based on surgeon preference and background. The true greatness and impact of the evolving field lies in the degree to which it can be safely disseminated to the masses through collaborative partnerships. If realized, this combination of enhanced safety and unrestricted practicality may lead to a significant rise in liver donation and a new era in LDLT.

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Footnote

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