ANNALS OF TRANSPLANTATION

ORIGINAL PAPER

e-ISSN 2329-0358
© Ann Transplant, 2026; 31: e953061
DOI: 10.12659/AOT.953061

Received: 2026.02.06
Accepted: 2026.06.08
Available online: 2026.07.09
Published: 2026.XX.XX

Learning Curve and Outcomes of Pure Laparoscopic Donor Major Hepatectomy Performed by Fellowship-Trained Surgeons: Cumulative Sum and Propensity Score Matching Analysis

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Financial support: None declared
Conflict of interest: None declared

Background: Pure laparoscopic donor major hepatectomy (PLDMH) offers important advantages for donors but has largely been restricted to expert surgeons. Evidence on fellowship-trained surgeons (FTSs) performing PLDMH after structured training is limited. This study evaluated donor safety and operative efficiency of FTSs using propensity score matching (PSM) and cumulative sum (CUSUM) analysis.

Material/Methods: We retrospectively reviewed 517 consecutive PLDMHs from 3 centers, including 1 expert surgeon (n = 462) and 3 FTSs (n = 55). FTSs underwent a structured, phase-task–based training program; 2 received short-term on-site proctorship for initial cases. To reduce baseline differences, we applied 1: 3 propensity score matching (PSM) between FTS and expert cases. Donor and recipient characteristics were balanced. Learning curves were assessed using risk-adjusted CUSUM for major donor complications and residual CUSUM for operative time.

Results: After PSM, 55 FTS cases were matched to 165 expert cases. Major donor complications were comparable (5.5% vs 4.2%, $P = 0.714$) and no case required conversion to open surgery. Donor operative time was longer in the FTS group (338 ± 102 vs 220 ± 44 minutes, $P < 0.001$). Recipient biliary leakage was more frequent in the FTS group (18.2% vs 8.5%, $P = 0.046$), whereas other outcomes were similar after matching. Risk-adjusted CUSUM demonstrated stabilization of donor safety within 8 to 10 cases per FTS, while operative efficiency stabilized after 6 to 15 cases.

Conclusions: FTSs demonstrated acceptable donor safety outcomes under structured training conditions, with operative performance showing a trend toward improvement after approximately 10 to 15 cases.

Keywords: **Hepatectomy • Laparoscopy • Learning Curve**

Full-text PDF: https://www.annalsoftransplantation.com/abstract/index/idArt/953061

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Indexed in: [Science Citation Index Expanded] [Index Medicus/MEDLINE] [Chemical Abstracts] [Scopus]

Introduction

Living donor liver transplantation (LDLT) is now established as a vital therapeutic option for patients with end-stage liver disease and hepatocellular carcinoma, providing an effective alternative to deceased donor transplantation. By addressing the shortage of cadaveric organs, LDLT enables timely surgical intervention, ensures optimal graft quality, and reduces waiting list mortality [1,2]. Innovations such as ABO-incompatible LDLT, dual grafts, and anonymous donation have further expanded its applicability. Throughout this progress, maintaining donor safety through rigorous selection protocols and leveraging the cumulative experience of high-volume centers remains paramount [3].

Pure laparoscopic donor hepatectomy (PLDH) has been developed as a safe, minimally invasive alternative to open donor hepatectomy (ODH). Multiple studies have demonstrated its advantages, including faster recovery, less postoperative discomfort, and superior cosmetic results [4,5]. Despite these advantages, the technical demands of PLDH require substantial expertise in both laparoscopic liver surgery and liver transplantation [6], which has restricted its successful implementation to specialized centers [7,8]. While pure laparoscopic donor left lateral sectionectomy for pediatric transplantation is now standard in experienced centers, pure laparoscopic donor major hepatectomy (PLDMH) for adult-to-adult living donor liver transplantation (ALDLT) remains limited to expert surgeons [9]. Previous studies have reported the learning curve of proctored pure laparoscopic donor left lateral sectionectomy for pediatric LDLT [10]; however, research focusing on the structured training of PLDMH for ALDLT is lacking. This gap underscores the challenge of educating the next generation of liver surgeons in this complex procedure, as minimally invasive techniques do not readily lend themselves to the traditional apprenticeship-based model of surgical training, which relies heavily on direct hands-on skill transfer.

In our clinical setting, which has fully transitioned from ODH to a laparoscopic approach [8], fellowship-trained surgeons (FTSs) were able to independently perform PLDMH after structured training and proctorship [11]. The aim of this study was to evaluate the safety and feasibility of PLDMH performed by FTSs with those of an expert surgeon through comparison of donor and recipient surgical outcomes using propensity score matching (PSM) and to assess the acquisition of proficiency by applying the cumulative sum (CUSUM) method.

Material and Methods

Ethics Statement

This study was approved by the institutional review boards of the Samsung Medical Center (2013-11-067-001) and Yeungnam University Medical Center (2023-10-055). At Hanyang University Medical Center, only de-identified retrospective data were analyzed in accordance with institutional policy and the Declaration of Helsinki.

Patients and Data

From December 2016 to December 2023, a total of 517 PLDMHs and ALDLTs were performed by 1 expert surgeon and 3 FTSs at Samsung Medical Center, Yeungnam University Medical Center, and Hanyang University Medical Center in South Korea. Clinical data for all donors and recipients were comprehensively reviewed from each center's prospectively maintained liver transplantation database. Preoperative, intraoperative, and postoperative 90-day donor outcomes, together with matched recipient outcomes within the 90-day postoperative period, were compared between 1 expert surgeon at Samsung Medical Center (expert group, n = 462) and 3 FTSs who were trained by this expert and subsequently initiated the PLDMH and LDLT programs at their respective hospitals (FTS group, n = 55). The primary endpoint of this study was donor safety, while operative performance and recipient outcomes were evaluated as secondary endpoints. After completing the fellowship program, 3 FTSs had diverse clinical settings: FTS 1 started the PLDH program at a small LDLT center (fewer than 20 liver transplants annually); FTS 2 started the program at 2 small LDLT centers due to relocating to another hospital; and FTS 3 performed PLDMH at the same center where training was received. FTS 1 and FTS 2 received proctorship from the expert surgeon, who visited their respective hospitals for the initial 7 and 8 cases, respectively.

Surgical Technique and Standardization of PLDMH

PLDMH was performed using a standardized, phase-based approach developed through a cognitive task analysis–based training framework, including predefined port placement, procedural phase segmentation, and task-specific actions, as previously described [11]. Briefly, the procedure is structured into 6 sequential phases: (1) right liver mobilization, (2) hilar structure identification, (3) parenchymal transection, (4) right hepatic duct division, (5) graft separation from the inferior vena cava, and (6) graft vasculature division. Each phase is executed in a predefined order with consistent roles assigned to the surgeon, assistant, and scopist to ensure procedural reproducibility. Parenchymal transection was performed along the ischemic demarcation line using energy devices and laparoscopic ultrasonic aspirator, with selective inflow control when necessary. Major vascular structures were dissected and divided using clips or vascular staplers according to standardized protocols. Particular attention was given to bile duct division, which was performed after precise anatomical identification using intraoperative imaging guidance to minimize biliary complications. Conversion to open surgery was considered based on predefined safety criteria, including uncontrolled bleeding, inability to safely control major vascular structures, unclear anatomical identification (particularly biliary anatomy), or any situation compromising donor safety. All procedures were performed with a low threshold for conversion when necessary.

Structured Training Program for FTSs

FTSs completed a 3-year intensive training program in liver transplantation and laparoscopic liver resection prior to performing independent PLDMH. During the latter 2 years of the program, structured training in laparoscopic liver resection was emphasized, including proctorship-based learning under expert supervision. The training followed a stepwise approach based on procedural segmentation, in which trainees initially participated in less complex and lower-risk components of the operation and progressively advanced to more technically demanding and critical steps. During the fellowship period, FTSs did not perform major anatomical liver resections independently from start to finish, with the exception of left lateral sectionectomy. Instead, they participated in selected phases of procedures across different cases to acquire phase-specific proficiency. Proctorship was not applied to donor hepatectomy during the training period, due to ethical considerations. After transitioning to independent practice, FTSs received limited expert guidance during their initial cases, particularly for donor-specific critical steps such as right hepatic duct isolation and division, which are not routinely encountered in standard laparoscopic liver resection. This structured training pathway was designed to ensure safe skill acquisition while maintaining strict donor safety principles.

Statistical Analysis

Statistical analyses were performed using R software (version 4.5.1; R Foundation for Statistical Computing, Vienna, Austria). To adjust for baseline differences, PSM was applied in a 1: 3 ratio between the FTS and expert groups using a nearest-neighbor matching method without replacement. The variables included in the propensity score model consisted of donor-related factors, such as sex, age, and body mass index; graft-related factors, including multiple hepatic arteries, dual portal veins, graft weight, cold ischemia time, warm ischemia time, and graft-to-recipient weight ratio (GRWR); and recipient-related factors, including sex, age, Child-Turcotte-Pugh score, Model for End-stage Liver Disease score, ABO incompatibility, and hepatocellular carcinoma. Covariate balance was assessed using standardized mean differences. CUSUM analyses, including risk-adjusted and residual methods, were used to evaluate donor safety and operative efficiency. Breakpoints were estimated by segmented regression with 95% confidence intervals (CIs), and interpreted as the number of cases required for surgeons to achieve stable performance. A 2-sided $P<0.05$ was considered statistically significant.

Results

Baseline Characteristics

During the study period, FTSs performed a total of 55 PLDMH (FTS 1: 16 cases; FTS 2: 20 cases; FTS 3: 19 cases) and ALDLT, while 1 expert surgeon conducted 462 cases of PLDMH and ALDLT. Baseline characteristics of donors, grafts, and recipients are summarized in **Table 1**. Before PSM, significant differences were observed between the FTS and expert groups in cold ischemic time (70±25 vs 91±48 minutes, $P=0.001$), GRWR (1.24±0.32 vs 1.08±0.27, $P<0.001$), recipient sex distribution (male 41.8% vs 71.9%, $P<0.001$), etiology of liver disease ($P=0.012$), presence of hepatocellular carcinoma (40% vs 66.2%, $P<0.001$), and Child-Turcotte-Pugh score (8±3 vs 7±2, $P=0.001$).

After 1: 3 PSM, 55 donors in the FTS group were matched with 165 in the expert group. The 2 groups were well balanced with no statistically significant differences in donor, graft, or recipient factors, including age, sex, body mass index, ischemic times, GRWR, graft type, vascular and biliary anatomy, and recipient demographics.

Donor and Recipient Outcomes

Postoperative donor and recipient outcomes are presented in **Table 2**. Neither the expert nor the FTS group required conversion to open surgery. Before PSM, the FTS group had significantly longer operative times for donors (338±102 vs 214±43 minutes, $P<0.001$) and recipients (474±87 vs 384±90 minutes, $P<0.001$). Recipient hepatic vein complications (5.5% vs 1.1%, $P=0.043$) and 90-day mortality (9.1% vs 2.4%, $P=0.020$) were also higher in the FTS group, whereas other complications, including bile leakage, biliary stricture, and vascular complications, did not differ significantly. Donor complications occurred in 7.3% of the FTS group and 14.7% of the expert group ($P=0.153$).

After 1: 3 PSM, donor operative time remained significantly longer in the FTS group (338±102 vs 220±44 minutes, $P<0.001$), while hospital stay, bile leakage, and overall complication rates were comparable between groups. Among recipients, operative time was again longer in the FTS group (474±87 vs 381±80 minutes, $P<0.001$). Importantly, biliary leakage was more frequent in the FTS group (18.2% vs 8.5%, $P=0.046$), whereas hepatic vein complications and 90-day mortality no longer showed significant differences. The

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Table 1. Preoperative and intraoperative characteristics of donors, grafts, and recipients between the fellowship-trained surgeon (FTS) and expert groups.

Characteristic	Before matching			After matching		
	FTS (n=55)	Expert (n=462)	*P* value	FTS (n=55)	Expert (n=165)	*P* value
Donor factors						
Donor age, years	38±13	37±14	0.622	38±13	38±13	0.941
Donor sex, male / female	34 (61.8%) / 21 (38.2%)	259 (56.1%) / 203 (43.9%)	0.473	34 (61.8%) / 21 (38.2%)	94 (57%) / 71 (43%)	0.636
Donor BMI, kg/m^2	25±4	24±3	0.073	25±4	24±3	0.298
Cold ischemic time, min	70±25	91±48	**0.001**	70±25	77±26	0.109
Warm ischemic time, min	46±20	42±16	0.221	46±20	44±18	0.639
Graft weight, g	754±162	729±144	0.242	754±162	741±148	0.578
GRWR, %	1.24±0.32	1.08±0.27	**<0.001**	1.24±0.32	1.15±0.29	0.053
Graft factors						
Graft type			0.191			0.603
Right / extended right	46 (83.6%) / 1 (1.8%)	242 (91.8%) / 9 (1.9%)		46 (83.6%) / 1 (1.8%)	146 (88.5%) / 4 (2.4%)	
Left / extended left / Left tri	1 (1.8%) / 4 (7.3%) / 0	3 (0.6%) / 9 (1.9%) / 1 (0.2%)		1 (1.8%) / 4 (7.3%) / 0	1 (0.6%) / 3 (1.8%)	
Right posterior	3 (5.5%)	16 (3.5%)		3 (5.5%)	10 (6.1%)	
Left trisection	0	1 (0.2%)		0	1 (0.6%)	
Hepatic artery type			0.763			0.547
Normal	49 (89.1%)	305 (84.6%)		49 (89.1%)	140 (84.8%)	
Variation of left / right	1 (1.8%) / 5 (9.1%)	19 (4.1%) / 50 (10.8%)		1 (1.8%) / 5 (9.1%)	6 (3.6%) / 19 (11.5%)	
Variation of both	0	2 (0.4%)		0	0	
Multiple hepatic artery	1 (1.8%)	5 (1.1%)	<0.999	1 (1.8%)	4 (2.4%)	<0.999
Portal vein type			0.717			0.722
I / II	48 (87.3%) / 2 (3.6%)	398 (86.1%) / 27 (5.8%)		48 (87.3%) / 2 (3.6%)	139 (84.2%) / 12 (7.3%)	
III / other type	5 (9.1%) / 3 (6.9%)	0 / 5 (1.1%)		5 (9.1%) / 3 (6.9%)	11 (6.7%) / 3 (1.8%)	
Dual portal vein	1 (1.8%)	23 (5%)	0.352	1 (1.8%)	6 (3.6%)	0.683
Bile duct type			0.611			0.947
I	33 (60%)	355 (76.8%)		33 (60%)	122 (73.9%)	
II / III	14 (25.5%) / 5 (9.1%)	11 (2.4%) / 54 (11.7%)		14 (25.5%) / 5 (9.1%)	8 (4.8%) / 16 (9.7%)	
IV / V / others	1 (1.8%) / 1 (1.8%) / 1 (1.8%)	33 (7.1%) / 2 (0.4%) / 7 (1.5%)		1 (1.8%) / 1 (1.8%) / 1 (1.8%)	14 (8.5%) / 2 (1.2%) / 3 (1.8%)	
Multiple bile duct	20 (36.4%)	118 (25.5%)	0.106	20 (36.4%)	48 (29.1%)	0.400

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Table 1 continued. Preoperative and intraoperative characteristics of donors, grafts, and recipients between the fellowship-trained surgeon (FTS) and expert groups.

Characteristic	Before matching			After matching		
	FTS (n=55)	Expert (n=462)	*P* value	FTS (n=55)	Expert (n=165)	*P* value
Recipient factors						
Recipient age, years	55±8	56±9	0.802	55±8	57±7	0.377
Recipient sex, male/female	23 (41.8%) / 32 (58.2%)	332 (71.9%) / 130 (28.1%)	**<0.001**	23 (41.8%) / 32 (58.2%)	94 (57%) / 71 (43%)	0.051
Etiology of recipient			**0.012**			0.358
Hepatitis B virus	21 (38.2%)	274 (59.3%)		21 (38.2%)	83 (50.3%)	
Hepatitis C virus	2 (1.6%)	14 (3%)		2 (1.6%)	4 (2.5%)	
Alcohol	21 (38.2%)	95 (20.6%)		21 (38.2%)	38 (23%)	
Others	11 (20%)	79 (17.1%)		11 (20%)	40 (24.2%)	
ABO incompatible	10 (18.2%)	123 (26.7%)	0.195	10 (18.2%)	40 (24.2%)	0.458
Hepatocellular carcinoma	22 (40%)	306 (66.2%)	**<0.001**	22 (40%)	87 (52.7%)	0.120
Mean MELD score	15±9	14±8	0.199	15±9	14±7	0.449
Mean CTP score	8±3	7±2	**0.001**	8±3	8±2	0.111

Characteristics highlighted in bold were included as matching variables in the propensity score analysis. *P* values highlighted in bold demonstrate a statistically significant difference on univariable analysis. Abbreviations: FTS, fellowship-trained surgeon; BMI, body mass index; GRWR, graft-to-recipient weight ratio; MEDL, Model for End-Stage Liver Disease; CTP, Child-Turcotte-Pugh.

overall distribution of postoperative complications according to the Clavien-Dindo classification was similar between groups after matching.

Learning Curve Analysis

Risk-adjusted CUSUM analysis demonstrated early trends toward stabilization of donor safety within 10 to 15 cases for all FTSs. FTS 1 reached stabilization at case 8 (95% CI, 6-11), FTS 2 at case 10 (95% CI, 7-14), and FTS 3 at case 9 (95% CI, 7-10). The expert surgeon maintained stable outcomes across the entire series, with late breakpoints beyond 150 cases (**Figure 1**). This breakpoint reflects a change in performance trend rather than a learning threshold.

Residual CUSUM analysis of operative time demonstrated a similar pattern of improvement over time. Breakpoints were estimated at case 6 (95% CI, 6-10) for FTS 1, case 14 (95% CI, 10-15) for FTS 2, and case 6 (95% CI, 6-8) for FTS 3 (**Figure 2**).

Crude CUSUM analysis of operative time compared the expert surgeon's initial 55 cases (mean 278 minutes) with those of the 3 FTSs. Each curve represents the deviation from the surgeon-specific mean operative time. The shaded area (cases 10-15) indicates the approximate range in which efficiency improvement was observed for all FTSs. The expert's early 55 cases demonstrated an initial rise followed by subsequent plateauing, consistent with early learning effects. All FTSs showed similar patterns of early operative time prolongation with subsequent stabilization. Mean operative times are indicated in the figure legend for each group (**Figure 3**).

Discussion

PLDH represents a landmark achievement in the field of LDLT, standing out as a significant technological advancement. It is particularly notable for its complexity and technical demands. A minimally invasive approach to donor surgery is ideal for liver donation in healthy individuals. This method offers potential benefits such as a faster return to normal activities and minimal upper abdominal scarring for the donor, which can also help reduce the recipient's feelings of guilt [12].

The introduction of PLDH for living donor surgery has posed new challenges in training the next generation of surgeons, similar to other surgical fields. Advances in surgical instruments, including 3-dimensional cameras and energy devices, have shifted the focus of minimally invasive surgery from tactile proficiency to visual learning, thereby necessitating new

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Table 2. Postoperative outcomes of donors and recipients between the fellowship-trained surgeon (FTS) and expert groups.

Outcomes	Before matching			After matching		
	FTS (n=55)	Expert (n=462)	*P* value	FTS (n=55)	Expert (n=165)	*P* value
Donor outcomes						
Operation time, min	338±102	214±43	**<0.001**	338±102	220±44	**<0.001**
Hospital stay, days	8±2	8±2	0.940	7.7±2.5	7.8±2.3	0.854
Portal vein stricture	0 (0%)	1 (1.2%)	1.000	0	0	n/a
Bile leakage	3 (5.5%)	11 (2.4%)	0.179	3 (5.5%)	3 (1.8%)	0.167
Complication	4 (7.3%)	68 (14.7%)	0.153	4 (7.3%)	24 (14.5%)	0.242
Major complication (≥III)	3 (5.5%)	21 (4.5%)	0.733	3 (5.5%)	7 (4.2%)	0.714
Clavien-Dindo classification			0.265			0.294
Grade I	0	1 (0.2%)		0	0	
Grade II	1 (1.8%)	46 (10%)		1 (1.8%)	16 (9.7%)	
Grade IIIa	2 (3.6%)	15 (3.2%)		2 (3.6%)	3 (1.8%)	
Grade IIIb	1 (1.8%)	6 (1.3%)		1 (1.8%)	5 (3.0%)	
Recipient outcomes						
Operation time, min	474±87	384±90	**<0.001**	474±87	381±80	**<0.001**
Hepatic artery complication	1 (1.8%)	24 (5.2%)	0.346	1 (1.8%)	24 (5.2%)	0.346
Portal vein complication	4 (7.3%)	20 (4.3%)	0.497	4 (7.3%)	4 (2.4%)	0.110
Hepatic vein complication	3 (5.5%)	5 (1.1%)	0.043	3 (5.5%)	2 (1.2%)	0.101
Bile leakage	10 (18.2%)	43 (9.3%)	0.179	10 (18.2%)	14 (8.5%)	**0.046**
Bilie duct stricture	12 (21.8%)	129 (27.9%)	0.496	12 (21.8%)	37 (22.4%)	0.862
90-day mortality	5 (9.1%)	11 (2.4%)	**0.020**	5 (9.1%)	8 (4.8%)	0.319
Clavien-Dindo classification			0.174			0.206
Grade I/II	6 (10.9%) / 4 (7.3%)	5 (1.1%) / 76 (16.5%)		6 (10.9%) / 4 (7.3%)	1 (0.6%) / 31 (18.8%)	
Grade IIIa/IIIb	16 (29.1%) / 3 (5.5%)	88 (19%) / 58 (12.6%)		16 (29.1%) / 3 (5.5%)	32 (19.4%) / 18 (10.9%)	
Grade IV	0	4 (0.8%)		0	1 (0.6%)	
Grade V	5 (9.1%)	11 (2.4%)		5 (9.1%)	4 (2.4%)	

P values highlighted in bold demonstrate a statistically significant difference on univariable analysis.

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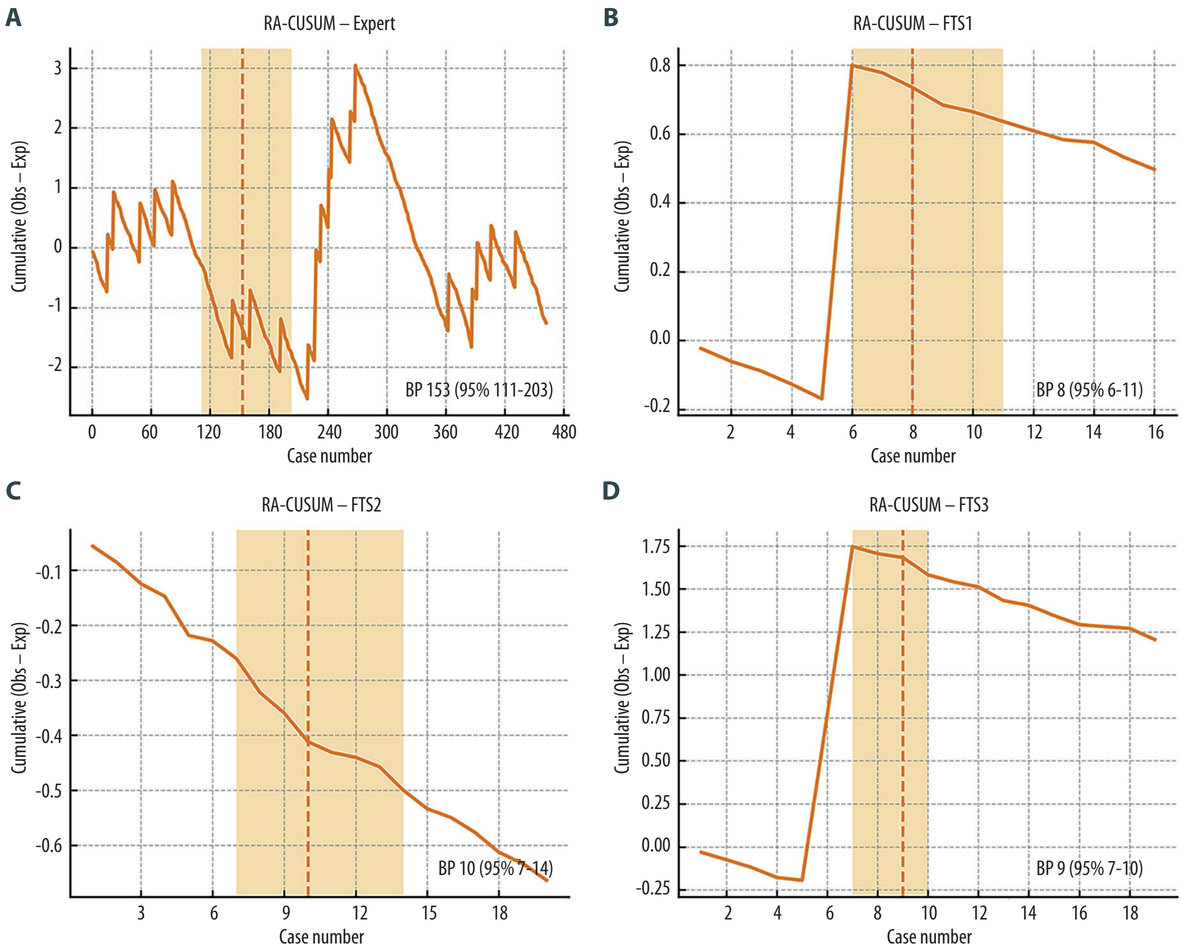

Figure 1. Risk-adjusted cumulative sum (RA-CUSUM) analysis of major donor complications (Clavien-Dindo grade ≥III). Breakpoints were estimated by segmented regression with 95% confidence intervals.

educational strategies. Training has accordingly evolved to emphasize the contextual understanding of each surgical phase. The structured breakdown of complex procedures into defined operative phases facilitated consistent execution among new surgeons. Continuous access to operative recordings and peer review supported the refinement of technique, allowing reproducible outcomes even in the early learning period [13].

The primary aim of this study was to evaluate the safety and procedural performance in PLDMH performed by FTSs compared with that of an expert surgeon, using PSM and CUSUM analysis. Donor safety outcomes were comparable between groups; although operative time in the FTS group was significantly longer, there were no conversions to open surgery, and the incidence of major complications (≥grade III) was similar. Although step-specific operative time data were not available, the prolonged operative time in the FTS group is likely attributable to technically demanding phases of the procedure, particularly parenchymal transection and bile duct division, which require advanced technical proficiency and careful anatomical interpretation. Several reports have addressed the learning curve of PLDH, and studies focusing on pure laparoscopic donor left lateral sectionectomy for pediatric transplantation have suggested that proficiency may be achieved after roughly 25 procedures [10]. For PLDH in ALDLT, it has been reported that the standardization of surgical skills typically requires 50 to 70 cases to achieve a stable learning curve [14,15]. However, these studies were based on PLDH performed by expert surgeons. To the best of our knowledge, the present study is the first CUSUM analysis of PLDMH for ALDLT between an expert and FTSs. Notably, FTSs who underwent structured education using a systematic phase-task approach achieved operative efficiency after only 10 to 15 cases, which is considerably faster than previous reports [16]. Interestingly, operative time for FTS 2 increased temporarily following relocation to a new center but subsequently stabilized, while FTS 3 demonstrated the most rapid stabilization despite the absence of direct expert guidance. These findings highlight the importance

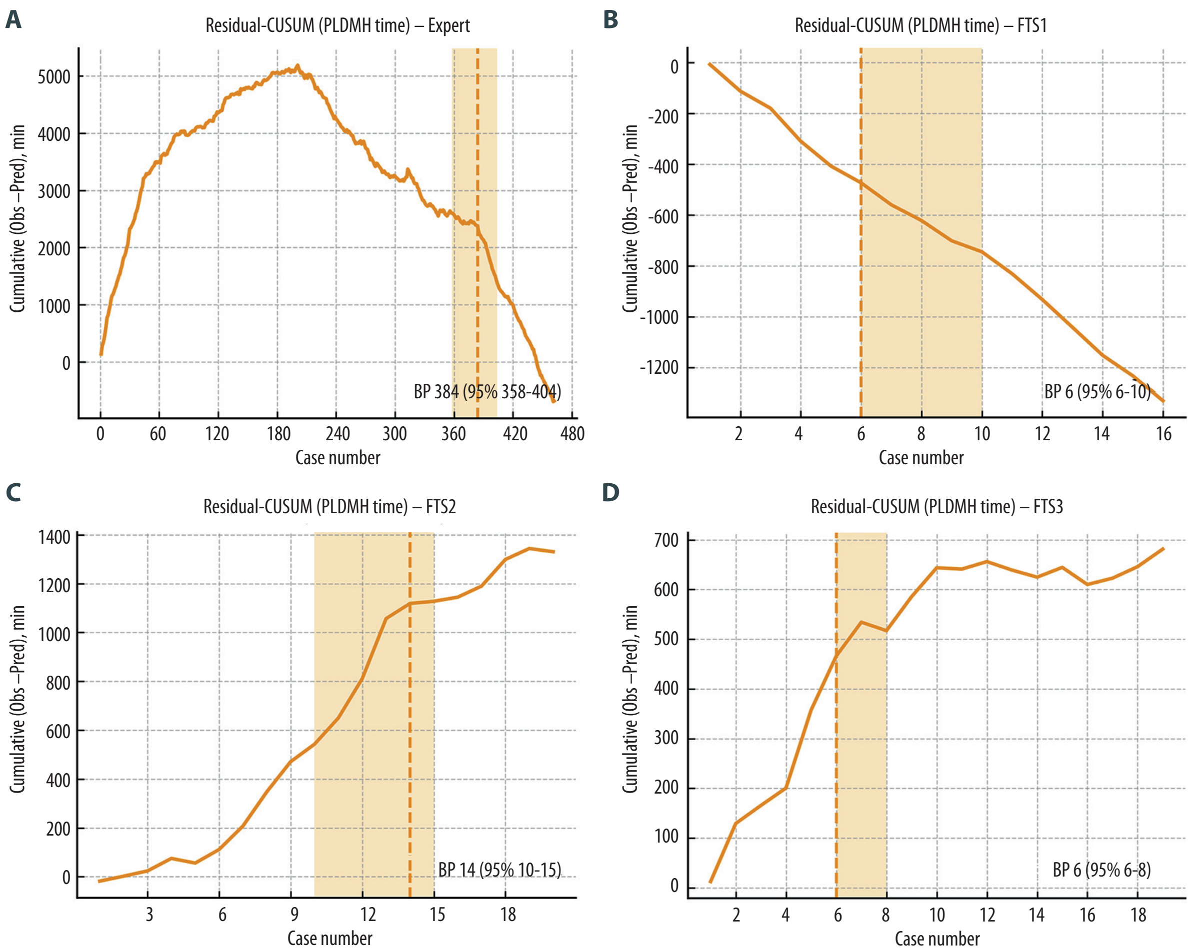

Figure 2. Residual cumulative sum (CUSUM) analysis of operative time for fellowship-trained surgeons (FTSs 1-3) compared with the expert surgeon. Vertical dashed lines indicate estimated breakpoints (segmented regression, 95% confidence intervals).

of standardized team practices within each center, including the proficiency of anesthesiologists, scrub nurses, scopists, and assistants, in addition to structured surgical education [8].

Direct expert supervision during the early implementation phase played a pivotal role in maintaining procedural safety and ensuring adherence to standardized techniques across centers. However, because proctorship can sometimes be perceived as a form of surrogate surgery, it carries potential risks to patient safety and raises ethical considerations. Given these ethical constraints inherent to donor surgery, early operative participation was restricted to predefined procedural phases under strict supervision to ensure donor safety during the transition to independent practice. Throughout the training process at our center, FTSs never performed a major laparoscopic liver resection independently from start to finish. Instead, by mastering key actions within distinct surgical phases across various clinical scenarios, they developed sufficient technical competence to perform their initial independent procedures safely. In donor surgery, it is ethically inappropriate for trainees to undertake critical operative steps in place of the attending surgeon; therefore, no proctorship involving donor surgery was permitted during FTS training. These findings indicate that, after structured preparation in major laparoscopic liver resections, FTSs can safely perform PLDMH without prior experience in ODH. Nevertheless, expert guidance remains indispensable during critical phases, particularly during bile duct division.

This study has several limitations. First, recipient outcomes in the FTS group were inferior to those in the expert group, including a higher incidence of biliary complications, likely reflecting the influence of institutional volume rather than donor graft quality. This finding is clinically meaningful and warrants careful interpretation when considering the overall safety of LDLT in the context of FTS implementation. While this difference may raise concerns, it is unlikely to be solely attributable to donor surgical factors or graft quality, given that standardized procurement techniques were applied across groups.

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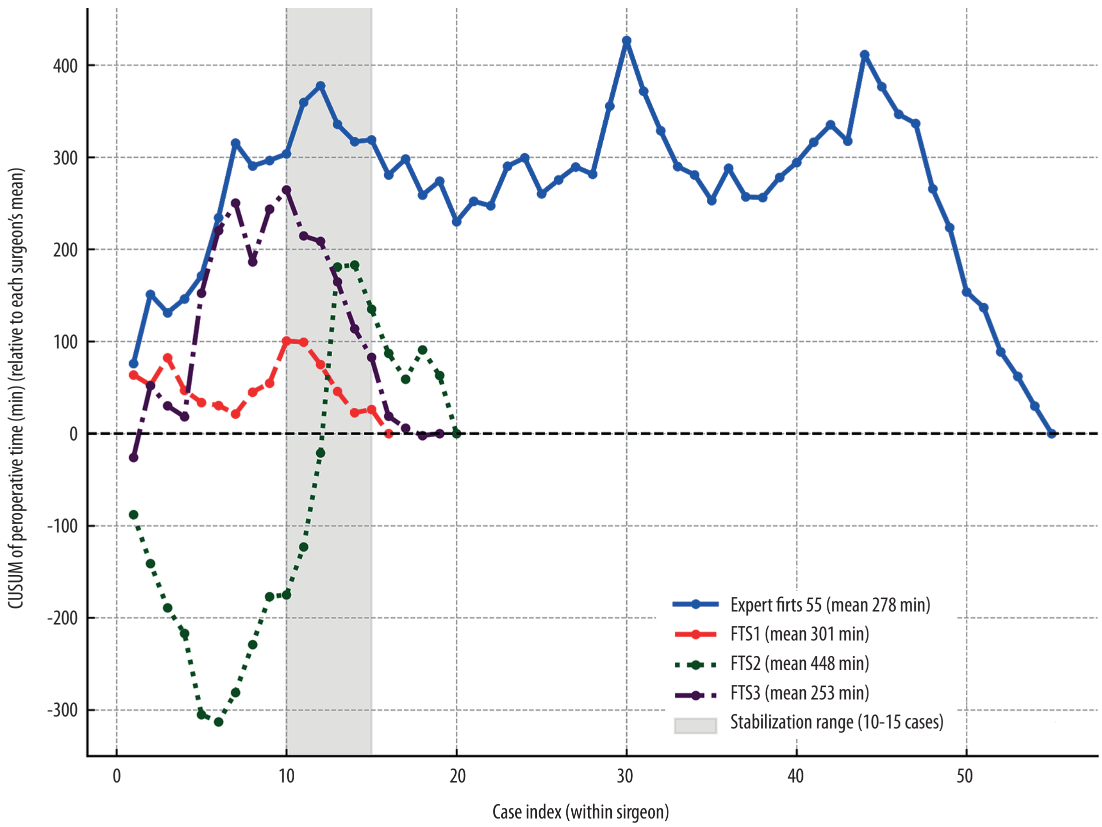

Figure 3. Crude cumulative sum (CUSUM) analysis of operative time comparing the expert surgeon's initial 55 cases (mean, 278 minutes) with fellowship-trained surgeons (FTSs 1-3). The shaded area (cases 10-15) denotes the approximate range of efficiency stabilization.

Previous research has demonstrated that high-volume centers (> 50 LDLTs annually) achieve superior results, including lower in-hospital mortality and improved long-term survival, compared with smaller centers [17,18]. However, comparable results may be attainable in small-volume centers through integrated training systems and protocol-based frameworks [19,20]. Due to the retrospective nature of this study, a strict classification of individual recipient complications according to their underlying cause (donor-related, graft-related, or recipient-related) was not feasible. Second, there is no objective certification system to validate the proficiency of FTSs after structured education, making it premature to revise current expert consensus guidelines, which state that PLDMH should be performed only by surgeons experienced in both laparoscopic liver surgery and liver transplantation. Finally, this study analyzed procedures performed by only 3 FTSs in heterogeneous practice environments, each performing fewer than 20 cases, thereby limiting the generalizability of our findings. Residual confounding related to institutional volume, team experience, and perioperative infrastructure cannot be fully excluded, despite the use of PSM. In addition, the relatively small number of cases per surgeon should be considered when interpreting the learning curve analysis. Accordingly, the CUSUM-derived breakpoints are better understood as reflecting early performance trends rather than definitive evidence of learning curve stabilization. Larger studies with long-term follow-up are needed to confirm these findings.

Conclusions

In conclusion, PLDMH performed by FTSs demonstrated acceptable donor safety outcomes under structured training conditions. Donor safety was maintained, and operative performance showed a trend toward improvement after approximately 10 to 15 procedures. These findings suggest that PLDMH may be implemented in selected settings with structured training, although further validation is required before broader generalization. Further multicenter studies with larger cohorts and long-term follow-up are warranted to evaluate recipient outcomes more comprehensively.

Indexed in: [Science Citation Index Expanded] [Index Medicus/MEDLINE] [Chemical Abstracts] [Scopus]

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Declaration of Figures' Authenticity

All figures submitted have been created by the authors who confirm that the images are original with no duplication and have not been previously published in whole or in part.

References:

1. Broelsch CE, Frilling A, Testa G, Malago M. Living donor liver transplantation in adults. Eur J Gastroenterol Hepatol. 2003;15:3-6
2. Abu-Gazala S, Olthoff KM. Current status of living donor liver transplantation in the United States. Annu Rev Med. 2019;70:225-38
3. Goldaracena N, Barbas AS. Living donor liver transplantation. Curr Opin Organ Transplant. 2019;24:131-37
4. Cho CW, Choi GS, Kim JM, et al. Postoperative health status and quality of life after pure laparoscopic donor hepatectomy for living donor liver transplantation. Ann Transplant. 2022;27:e935611
5. Han ES, Lee KW, Suh KS, et al. Shorter operation time and improved surgical outcomes in laparoscopic donor right hepatectomy compared with open donor right hepatectomy. Surgery. 2021;170:1822-29
6. Kim KH, Kang SH, Jung DH, et al. Initial outcomes of pure laparoscopic living donor right hepatectomy in an experienced adult living donor liver transplant center. Transplantation. 2017;101:1106-10
7. Hong SK, Kim JY, Lee J, et al. Pure laparoscopic donor hepatectomy: Experience of 556 cases at Seoul National University Hospital. Am J Transplant. 2024;24:222-38
8. Rhu J, Choi GS, Kim JM, et al. Complete transition from open surgery to laparoscopy: 8-year experience with more than 500 laparoscopic living donor hepatectomies. Liver Transpl. 2022;28:1158-72
9. Au KP, Chok KSH. Minimally invasive donor hepatectomy, are we ready for prime time? World J Gastroenterol. 2018;24:2698-709
10. Broering DC, Berardi G, El Sheikh Y, et al. Learning curve under proctorship of pure laparoscopic living donor left lateral sectionectomy for pediatric transplantation. Ann Surg. 2020;271:542-48
11. Cho CW, Rhu J, Kim KS, et al. Cognitive task analysis-based education and expansion of pure laparoscopic donor hepatectomy for the next generation: A comparative study of surgical outcomes between expert and fellowship-trained surgeons. Surg Endosc. 2026;40(2):1694-703
12. Ordin YS, Karayurt O, Aksu Kul G, et al. Exploration into donor-recipient relationship after living-donor liver transplantation using gift-exchange theory. Florence Nightingale J Nurs. 2021;29:150-57
13. Wingfield LR, Kulendran M, Chow A, et al. Cognitive task analysis: Bringing olympic athlete style training to surgical education. Surg Innov. 2015;22:406-17
14. Rhu J, Choi GS, Kwon CHD, et al. Learning curve of laparoscopic living donor right hepatectomy. Br J Surg. 2020;107:278-88
15. Hong SK, Suh KS, Yoon KC, et al. The learning curve in pure laparoscopic donor right hepatectomy: A cumulative sum analysis. Surg Endosc. 2019;33:3741-48
16. Halls MC, Alseidi A, Berardi G, et al. A comparison of the learning curves of laparoscopic liver surgeons in differing stages of the IDEAL paradigm of surgical innovation: standing on the shoulders of pioneers. Ann Surg. 2019;269:221-28
17. Edwards EB, Roberts JP, McBride MA, et al. The effect of the volume of procedures at transplantation centers on mortality after liver transplantation. N Engl J Med 1999;341:2049-53
18. Yoo S, Jang EJ, Yi NJ, et al. Effect of institutional case volume on in-hospital mortality after living donor liver transplantation: Analysis of 7073 cases between 2007 and 2016 in Korea. Transplantation. 2019;103:952-58
19. Yeow M, Pang NQ, Chen Z, et al. Evaluation of adult living donor liver transplantation in largest Southeast Asian transplantation center: Benchmarking with adult-to-adult living donor liver transplantation (A2ALL) Experience. Transplant Proc. 2021;53:2953-62
20. Choi Y, Choi HJ, Park H, et al. Proposal of a network system to solve the problem of small volume in liver transplantation; Catholic Medical Center Network. Transplant Proc. 2024;56:640-56