ASTR

ORIGINAL ARTICLE
pISSN 2288-6575 • eISSN 2288-6796
https://doi.org/10.4174/astr.2024.107.2.81
Annals of Surgical Treatment and Research

Learning curve analysis for hand-assisted laparoscopic living donor nephrectomy: an analysis of 96 consecutive cases performed by a trained gastrointestinal surgeon

Chang In Choi[1,2], Kyeong Jun Lee[3], Min Joo Kim[1,2], Jae-Kyun Park[1,2], Da Woon Kim[2,4], Hyo Jin Kim[2,4], Harin Rhee[2,4], Sang Heon Song[2,4], Eun Young Seong[2,4], Dae-Hwan Kim[1,2], Tae Yong Jeon[1,2], Hyuk Jae Jung[1,2]

[1]Department of Surgery, Pusan National University School of Medicine, Busan, Korea
[2]Biomedical Research Institute, Pusan National University Hospital, Busan, Korea
[3]Department of Mathematics and Big Data Science, Kumoh National Institute of Technology, Gumi, Korea
[4]Division of Nephrology, Department of Internal Medicine, Pusan National University School of Medicine, Busan, Korea

Purpose: This study aims to analyze the learning curve of hand-assisted laparoscopic living donor nephrectomy (HLDN) conducted by a trained gastrointestinal surgeon.
Methods: A retrospective analysis was performed on the perioperative clinical data of 96 consecutive patients who underwent HLDN from May 2013 to March 2023. The learning curve was evaluated using the cumulative sum (CUSUM) test based on operation time and risk-adjusted CUSUM for postoperative complications. Patients were divided into three groups (novice, development, and competency phases) based on changes in operation time. Patient demographics and perioperative outcomes were compared between each group.
Results: Among the patients, 35 were male, with a mean age of 48.9 ± 11.3 years and a mean body mass index (BMI) of 24.5 ± 3.2 kg/m^2. The novice phase (phase 1) included the first 30 cases, with the development phase (phase 2) up to the 65th case. Operation times were significantly different across phases, averaging 263.2 ± 33.4, 211.1 ± 34.4, and 161.1 ± 31.3 minutes for phases 1, 2, and 3, respectively ($P < 0.001$). Blood loss decreased gradually across phases (phase 1, 264.7 ± 144.4 mL; phase 2, 239.7 ± 166.3 mL; phase 3, 198.8 ± 103.5 mL), though not statistically significant. BMI impacted operation time only in phase 1. Overall postoperative complications occurred in 13 cases (Clavien-Dindo grade I, 4 cases; grade II, 9 cases), with no significant differences across phases.
Conclusion: HLDN can be safely performed by a trained gastrointestinal surgeon, with approximately 30 cases needed to achieve proficiency.
[Ann Surg Treat Res 2024;107(2):81-90]

Key Words: Laparoscopy, Learning curve, Minimally invasive surgical procedures, Nephrectomy

INTRODUCTION

Kidney transplantation is the final and optimal treatment for end-stage renal disease. Beyond conventional open donor nephrectomy, minimally invasive surgeries, such as laparoscopic, hand-assisted, and robot-assisted procedures have been widely adopted because of their advantages in terms of postoperative recovery and quality of life [1]. Hand-assisted

Received May 10, 2024, **Revised** June 9, 2024, **Accepted** June 22, 2024

Corresponding Author: Hyuk Jae Jung
Department of Surgery, Medical Research Institute, Pusan National University Hospital, 179 Gudeok-ro, Seo-gu, Busan 49241, Korea
Tel: +82-51-240-7238, **Fax:** +82-51-247-1365
E-mail: goodsight@pusan.ac.kr
ORCID: https://orcid.org/0000-0003-3407-5855

• This study was presented at the 54th Congress of The Korean Society of Endo-Laparoscopic & Robotic Surgery & 14th Internation Symposium (KSERS 2024) in Daejeon, Korea, on April 11–13, 2024.

laparoscopic surgery was performed in the early laparoscopic era as a bridge from open to total laparoscopic surgery. However, hand-assisted laparoscopic donor nephrectomy (HLDN) is still considered a good option for a minimally invasive approach because of the necessity of a mini-laparotomy to extract the entire kidney [2]. Although the location of mini-laparotomy varies among institutions, HLDN, as a minimally invasive surgery, has similar advantages such as lesser postoperative pain, better cosmesis, and faster recovery, than open surgery [3].

Although recent surgical trends have focused on patient quality of life after surgery, donor safety must remain a top priority in transplantation procedures. Therefore, transplant surgeons must possess a high level of technical training and clinical experience. The learning curve is a widely used concept for evaluating whether a surgeon has achieved proficiency in conducting surgery successfully. Beyond the learning curve, surgical efficiency increases, surgical time shortens, postoperative complication occurrences reduce, and surgery becomes safer. The cumulative sum (CUSUM) analysis is a graphical methodology for solving industrial problems originally. It was developed to monitor surgical performance and is widely used to evaluate overcoming the learning curves [4-6]. Assessing the learning curve of surgery can be an excellent guide for training and surgical planning for novice surgeons or institutions preparing for surgery.

Donor nephrectomies are typically performed by urologists. If general surgeons from the same department can perform donor nephrectomies as a team, similar to that done for donor hepatectomies, it can offer considerable advantages in establishing better cooperation in scheduling surgery and postoperative care. However, there are no reports on long-term surgical outcomes of donor nephrectomy by general surgeons. A previous study discussed the training process and initial experience with donor nephrectomy [7]. In this study, we aimed to analyze the postoperative learning curve of HLDN performed by general surgeons who completed a staged training program and report the timing and outcomes of achieving surgical proficiency.

METHODS

Ethical considerations

This study was approved by the Institutional Review Board (IRB) of Pusan National University Hospital (No. 2404-021-138). Some requirements for written consent were waived off by the IRB owing to the retrospective nature of this study.

Patients and data collection

In this retrospective comparative study, perioperative clinical data of 96 consecutive patients who underwent HLDN at Pusan National University Hospital from May 2013 to March 2023 were analyzed. All surgeries were performed by a single gastrointestinal surgeon trained in donor nephrectomy. The donor candidates visit the outpatient clinic prior to surgery, where they receive explanations about the purpose of the tests, the surgical procedure, and the expected postoperative course. Laboratory tests are performed to assess their basic physical status and transplantation compatibility. Cardiopulmonary function tests are performed to prepare for general anesthesia. Kidney scans and computed tomography urography can identify kidney volume, function, and anatomical structure, such as vasculature or ureter, as well as rule out other organ diseases. After all preoperative evaluations are completed, a multidisciplinary conference involving nephrologists, surgeons, clinical pathologists, and transplant coordinators is held. During this conference, the team discusses preoperative preparations, surgical approaches, methods, and postoperative management. Perioperative clinical data, including patient demographics (age, sex, body mass index [BMI], and comorbidity) and perioperative outcomes (operation time, blood loss, graft size, vessel size, warm ischemia time [WIT], harvesting direction, postoperative pain, and complications) were prospectively collected. Surgical time was defined as the duration from the first incision to wound closure. WIT is defined as the time taken from clamping the renal artery to placing the graft into a cold preservation solution. Postoperative pain was evaluated using the numerical rating scale (NRS). The NRS scores were collected and divided into 3 categories: weak (score 1–3), moderate (score 4–6), and severe (score 7–9). Postoperative complications were classified using the Clavien-Dindo classification (CDC) and defined as complications occurring within 90 days after the surgery.

Surgical procedure

Patients were placed under general anesthesia in an appropriate lateral decubitus and 45° flank position for optimal abdominal exposure. A 12-mm port for the laparoscope and two or three 5-mm ports along with a 7-cm hand port (Gelport, Applied Medical) were placed according to the direction of kidney harvesting. Carbon dioxide was maintained at an abdominal pressure of 15 mmHg. The procedure involved dissection of the peritoneum, mobilization of the colon, isolation of the gonadal and ureteral pedicles, and identification of the renal vein and artery before kidney extraction using the hand port. The ureter and renal arteries were divided using a Hem-o-Lok ligation clip (Weck Closure Systems, Teleflex Medical). The renal vein was transected using a 45-mm laparoscopic linear stapler (Signia, Medtronic) following the procedure previously described [7].

Learning curve assessment using the cumulative sum analysis

The primary aim of this study was to evaluate the learning curve of HLDN using the CUSUM analysis by focusing on operation time and postoperative complication occurrence. We calculated and visualized the CUSUM values for each variable using the formulae described in the subsequent section.

Cumulative sum for operation time

The CUSUM for the operation time ($CUSUM_{OT}$) was calculated as the CUSUM of the differences between each case's operation time and the overall mean operation time, represented mathematically as follows:

$$CUSUM_{OT} = \sum_{i=1}^{n}(x_i - \mu)$$

where x_i represents the operation time for the i^{th} case, and μ represents the mean operation time for all cases.

This analysis facilitated the detection of fluctuations in surgical performance over time, outlining the learning curve into novice, developmental, and competency phases based on operational efficiency. The transition between these phases was determined by analyzing the CUSUM plots of operation time, with significant shifts indicating progression in surgeon proficiency.

Cumulative sum for postoperative complication

The risk-adjusted CUSUM (RA-CUSUM) analysis was performed to monitor clinical outcomes over time, with a specific focus on the occurrence of surgical complications. RA-CUSUM adjusts for each patient's preoperative risk level and individually estimates the expected rate of complications. Subsequently, the graph obtained is modified based on the actual occurrence or absence of complications considering the risks related to each patient.

While the CUSUM method primarily assesses surgical proficiency by accumulating operative time data, the RA-CUSUM analysis effectively mitigates potential biases by incorporating individualized risk assessments of complications at the time of surgery along with the cumulative experience of the surgeon. To facilitate bias reduction, the RA-CUSUM employs multivariate logistic regression analysis by considering a multitude of variables that may influence the likelihood of surgical complications.

Within this analytical framework, $x_i = 1$ signifies the occurrence of a complication, whereas $x_i = 0$ denotes its absence. Additionally, τ symbolizes the observed frequency of event occurrences, and P_i reflects the calculated probability of encountering a complication, derived through multivariate logistic regression analysis. The factors used to calculate P-values were BMI, sex, American Society of Anesthesiologists physical status (ASA PS) classification, comorbidity, blood loss, and harvesting direction.

This analytical method can be expressed using the following formula:

$$\sum_{i=1}^{n}(x_i - \tau) + (-1)^{x_i}P_i$$

Proficiency classification

The surgeons' proficiency levels were classified into 3 groups based on the results of the CUSUM analyses.

Phase 1 (novice phase): This phase is characterized by the surgeon's early experiences with HLDN. In this phase, the operation time is expected to be longer and postoperative complications occur frequently until the surgeon becomes familiar with the procedure.

Phase 2 (development phase): In this phase, the operation time and occurrences of postoperative complications begin to decrease as the surgeon gains confidence and efficiency.

Phase 3 (competency phase): This phase is identified as the point where the operation time and occurrences of postoperative complications stabilize at levels lower than those of the other phases, indicating that the surgeon has overcome the learning curve and achieved consistent proficiency.

Significant shifts in the CUSUM plot determine the transition thresholds among these stages. A downward trend in operation time and postoperative complication occurrences reflects the skill acquisition and efficiency of the surgeon. In the CUSUM curve, each phase is labeled as "$Phase_{OT}$" or "$Phase_{RA}$" depending on $CUSUM_{OT}$ and RA-CUSUM values. However, the phases used in the comparison of patient demographics and perioperative outcomes among the 3 groups were based on only $CUSUM_{OT}$ values.

Statistical analysis

The learning curve was examined for trends and shifts in operation time and postoperative complication occurrences using $CUSUM_{OT}$ and RA-CUSUM values. Pearson correlation and logistic regression analyses were used to investigate the relationship between BMI and operative time. Descriptive statistics were used to summarize postoperative pain using the NRS scores and patient demographic and perioperative data. Continuous variables were analyzed using analysis of variance, and the values are presented as mean ± standard deviation. Additionally, Bonferroni *post-hoc* analysis was conducted to verify differences in means among the 3 groups. Categorical variables were compared using the chi-square and Fisher exact tests. Statistical significance was considered at a P-value of <0.05, with analyses conducted using specified statistical software such as R-4.0.4 (CRAN, https://cran.r-project.org/) and IBM SPSS Statistics ver. 22 (IBM Corp.).

RESULTS

Learning curve analysis

The learning curve for HLDN was evaluated using the CUSUM analysis by focusing on operation time ($CUSUM_{OT}$) and probability of postoperative complications (RA-CUSUM) as the primary metrics. This analysis was used to identify the number of cases required to overcome the learning curve during each phase.

In the $CUSUM_{OT}$ analysis, operation time showed a consistent increase in the first 30 cases ($Phase_{OT}$ 1). The curve subsequently flattened as the rate of increase in operation time reduced on entering $Phase_{OT}$ 2, followed by stabilization as the cumulative operative time decreased beyond the 65th case. The RA-CUSUM analysis revealed a high risk of postoperative complications in the 17th case ($Phase_{RA}$ 1). The incidence of complications gradually declined until the 56th case ($Phase_{RA}$ 2), after which stability was confirmed. The findings of the learning curve analysis are presented in Fig. 1.

Patient demographics

The study included 96 patients who were divided into 3 phases based on the $CUSUM_{OT}$ analysis: phase 1 (n = 30), phase 2 (n = 35), and phase 3 (n = 31). The mean age of the patients was 48.9 ± 11.3 years, increasing across phases. There was a significant difference between phases 1 and 3 (43.3 ± 11.4 *vs.* 53.6 ± 9.5, P = 0.001). The sex distribution was not statistically different among the groups; however, the proportion of female donors was higher than that of male donors, comprising approximately 60%–65.7%. The mean BMI was 24.5 ± 3.2 kg/m^2, with similar results observed in all the groups. The phase 1 group had as high as 70% ASA PS classification I, and the phase 3 group had as high as 90.3% ASA PS classification II (P < 0.001). The comorbidities also increased significantly from

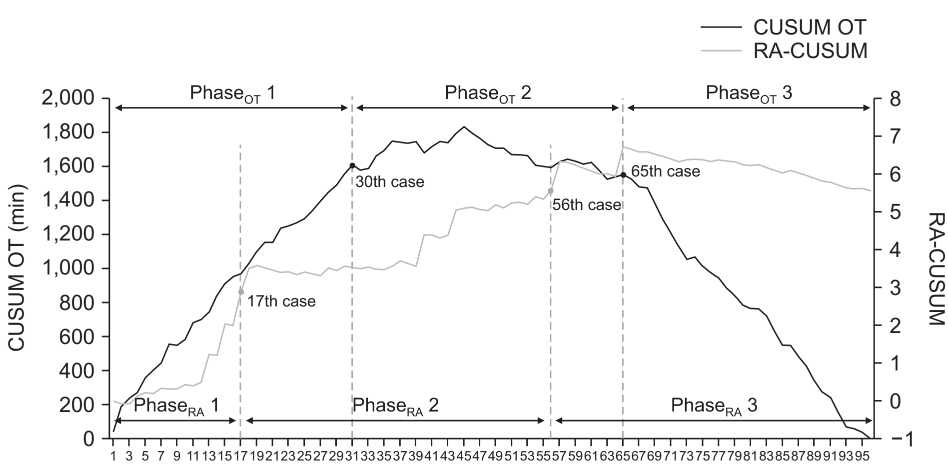

Fig. 1. The cumulative sum (CUSUM) chart. OT, operation time; RA-CUSUM, risk-adjusted CUSUM.

Table 1. Patients' demographics

Characteristic	Phase 1 (n = 30)	Phase 2 (n = 35)	Phase 3 (n = 31)	Overall (n = 96)	P-value
Age (yr)	43.3 ± 11.4[a]	49.6 ± 10.8[a, b]	53.6 ± 9.5[b]	48.9 ± 11.3	0.001 (a *vs.* b)
Sex					0.630
Male	12 (40.0)	12 (34.3)	11 (35.5)	35 (36.5)	
Female	18 (60.0)	23 (65.7)	20 (64.5)	61 (63.5)	
Body mass index (kg/m^2)	24.0 ± 3.1	25.0 ± 3.5	24.5 ± 2.9	24.5 ± 3.2	0.473
ASA PS classification[a)]					
I	21 (70.0)	12 (34.3)	3 (9.7)	36 (37.5)	<0.001
II	9 (30.0)	21 (60.0)	28 (90.3)	58 (60.4)	
III	0 (0)	2 (5.7)	0 (0)	2 (2.1)	
Comorbidity	3 (10.0)	8 (22.9)	14 (45.2)	25 (26.0)	0.006
Direction					0.141
Right	13 (43.3)	12 (34.3)	17 (54.8)	42 (43.8)	
Left	17 (56.7)	23 (65.7)	14 (45.2)	54 (56.3)	

Values are presented as number only, mean ± standard deviation, or number (%).
ASA PS, American Society of Anesthesiologists physical status.
[a)]Comparison between ASA PS classification I *vs.* II, III.
[a,b]The same superscript letters indicate nonsignificant differences between groups based on Bonferroni multiple comparison test.

Table 2. Perioperative data

Variable	Phase 1 (n = 30)	Phase 2 (n = 35)	Phase 3 (n = 31)	Overall (n = 96)	P-value
Operation time (min)	263.2 ± 33.4[a]	211.1 ± 34.4[b]	161.1 ± 31.3[c]	211.2 ± 52.4	<0.001 (a *vs.* b, b *vs.* c)
Blood loss (mL)	271.7 ± 190.1	220.0 ± 111.3	191.9 ± 99.2	227.1 ± 140.1	0.078
Graft weight (g)	155.9 ± 35.8	169.7 ± 39.8	168.1 ± 30.0	164.8 ± 35.7	0.262
Diameter (mm)					
Artery	4.3 ± 1.2[a]	4.5 ± 1.7[a, b]	5.8 ± 2.9[a, c]	4.8 ± 2.1	0.017 (b *vs.* c)
Vein	13.0 ± 3.2[a]	15.6 ± 4.8[b]	21.3 ± 3.9[c]	16.6 ± 5.3	<0.035 (a *vs.* b) <0.001 (a *vs.* c) <0.001 (b *vs.* c)
Warm ischemic time (min)	287.8 ± 108.6[a]	260.6 ± 64.1[a]	219.3 ± 68.4[b]	255.8 ± 85.5	0.005 (a *vs.* b)
Anatomical variation	7 (23.3)	9 (25.7)	4 (12.9)	20 (20.8)	0.406
Hospital stay (day)	7.3 ± 1.7[a]	6.8 ± 1.5[a, b]	5.7 ± 0.9[c]	6.6 ± 1.6	<0.001 (a *vs.* c) 0.007 (b *vs.* c)
Morbidity	6 (20.0)	7 (20.0)	0 (0)	13 (13.5)	0.028

Values are presented as mean ± standard deviation or number (%).
[a,b,c]The same superscript letters indicate a nonsignificant difference between groups based on Bonferroni multiple comparison test.

Table 3. Postoperative complication

Grade	Phase 1 (n = 30)	Phase 2 (n = 35)	Phase 3 (n = 31)	Overall (n = 96)	P-value
No complication	24 (80.0)	28 (80.0)	31 (100)	83 (86.5)	0.013[a)]
CDC grade					
I	2 (6.7) Cr elevation 1 Wound seroma 1	2 (5.7) Wound seroma 2	0 (0)	4 (4.2)	
II	4 (13.3) Chyle leakage 3 Ileus 1	5 (14.3) Chyle leakage 4 Wound infection 1	0 (0)	9 (9.4)	0.067[b)]

Values are presented as number (%).
CDC, Clavien-Dindo classification.
[a)]Overall complication rate comparison among the groups. [b)]Comparison of complication rate more than grade II. There was no significant difference in the overall and grade II complication rates among the groups (Fisher exact test).

10% in phase 1 to 45.2% in phase 3 (P = 0.006). The patient demographics are shown in Table 1.

Perioperative outcomes

Operation times significantly decreased over the phases, from 263.2 ± 33.4 minutes in phase 1 to 161.1 ± 31.3 minutes in phase 3 (P < 0.001). The mean operation time was 211.2 ± 52.4 minutes. The operation times in phases 1, 2, and 3 were 263.2 ± 33.4, 211.1 ± 34.4, and 161.1 ± 31.3 minutes, respectively. There were significant differences in the operation times in each phase (P < 0.001). The mean blood loss was 227.1 ± 140.1 mL and showed a decrease over the phases; however, there was no significant difference in the mean blood loss among the groups (P = 0.078). The mean WIT was 255.8 ± 85.5 minutes, with a significant difference between phases 1 and 3 (287.8 ± 108.6 minutes *vs.* 219.3 ± 68.4 minutes, P = 0.005). The mean hospital stay was 6.6 ± 1.6 days, and it gradually decreased over the phases (7.3 ± 1.7 days *vs.* 6.8 ± 1.5 days *vs.* 5.7 ± 0.9 days); however, there were no significant differences in the mean hospital stay between phases 1 and 2.

Postoperative complications were documented in 13 of 96 patients (13.5%). The overall complication rates did not differ significantly among the phases (P = 0.461). CDC grade I and II complications were reported in 4.2% (4 of 96) and 9.4% (9 of 96) of cases, respectively. There were no major complications greater than grade III, with no significant differences noted in the occurrence of grade II complications over the phases (P = 0.274). Most grade II complications were chyle leakages: 3 cases (10.0%) in phase 1 and 4 (11.4%) in phase 2. All the patients recovered well and were subsequently discharged. In phase 3, we could not identify any postoperative complications. There was no postoperative mortality in all cases. Perioperative outcomes and details of postoperative complications are presented in Tables 2 and 3, respectively.

Influence of body mass index on operation time

The operation time and BMI changes for each case are shown in Fig. 2. While the BMI distribution remained relatively consistent without notable fluctuations, the operation time gradually decreased in sequential cases. As shown in the $CUSUM_{OT}$ chart, the operation time started to fall below the mean in the 31st patient and gradually widened its distance from the BMI curve. This divergence of the operation time and BMI trajectory indicates that the proficiency level has entered a "transition" stage characterized by the operation times oscillating around the mean value. Subsequently, we confirmed that the surgeon had completed phase 2 by settling below the mean value.

No statistically significant correlation was observed between BMI and operative time in any case (P = 0.184). However, in the comparison among phases, phase 1 showed a weak positive correlation with increasing operation time for higher BMI (Pearson correlation coefficient = 0.408, P = 0.025). In phases 2 and 3, there was no correlation between these 2 factors, indicating that the surgeon's increasing proficiency mitigated the influence of BMI on the operation time (Fig. 3).

Trends in postoperative pain

The NRS scores for postoperative pain are shown in Fig. 4. In all phases, the pain intensity on postoperative day (POD) 1 was high, and the pain improved significantly around discharge. As HLDN is a minimally invasive approach, only mild pain remains at the time of discharge in most cases. However, the distribution of mild pain on POD 1 was 46.7% (14 of 30) in phase 1, 48.6% (17 of 35) in phase 2, and 67.7% (21 of 31) in phase 3. With an increase in surgical experience, immediate postoperative pain tended to decrease; however, the difference was not statistically significant.

DISCUSSION

Organ transplantation inherently has the characteristics of a paired procedure because of the presence of both the donor and recipient. As the liver is an intraabdominal organ, harvesting and implantation are performed by the same team during liver transplantation. In contrast, kidney transplantation requires a multidisciplinary approach because urologists mostly perform nephrectomies because of the retroperitoneal location of the

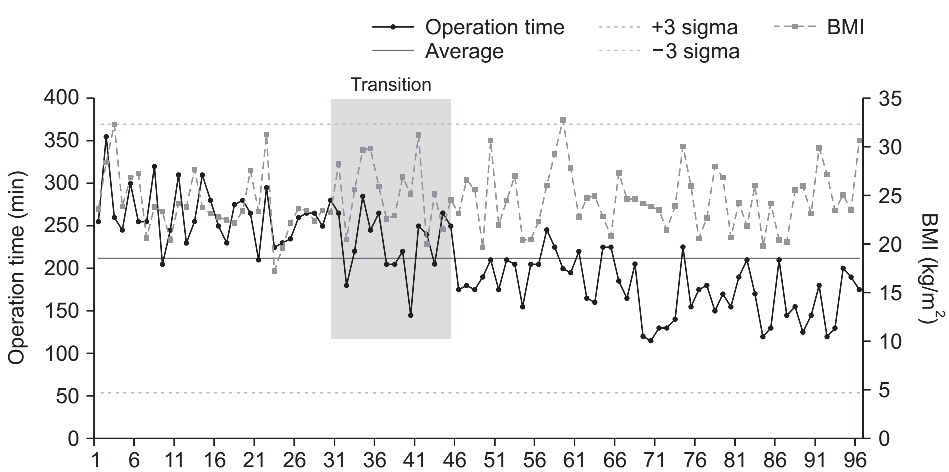

Fig. 2. Changes in the operation time and body mass index (BMI) according to the cases.

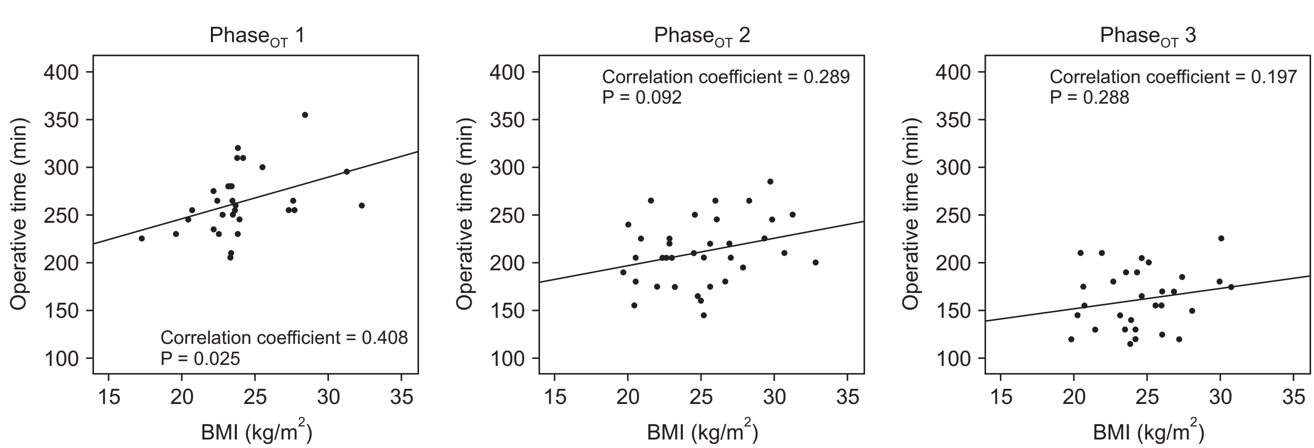

Fig. 3. Relation between the operation time and body mass index (BMI).

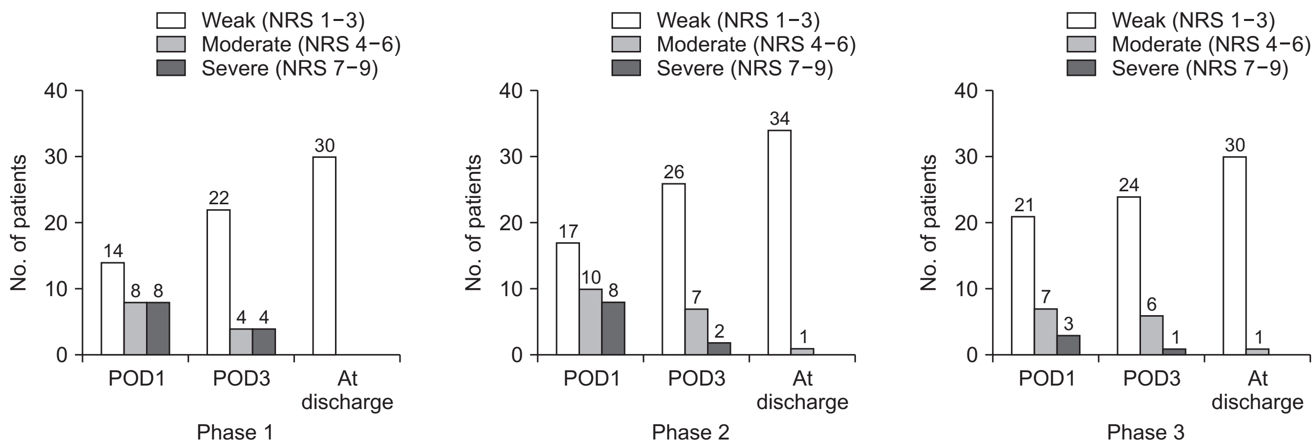

Fig. 4. Changes in postoperative pain. POD, postoperative day.

kidney and its disease entity. Although this multidisciplinary approach has its advantages, a unified surgical team may yield benefits in terms of more efficient management of the surgical schedule and postoperative care. Cadaveric kidney harvesting is typically performed by transplant surgeons. Surgeons who have operated on abdominal organs or have experience with retroperitoneal organs can learn kidney harvesting techniques through a systematic training program. When laparoscopic surgery was first introduced, HLDN was performed as a bridge surgery connecting open surgery with laparoscopic techniques. In recent years, the surgical approach has moved towards totally laparoscopic procedures, leading to a gradual decline in the use of HLDN. However, since mini-laparotomy is still necessary for kidney extraction without any injury during donor nephrectomy, HLDN still is being utilized in many institutions. It has still significant value as a transitional surgery in the progression toward fully laparoscopic methods. Although the mini-laparotomy located on the abdomen in the present study might be disadvantageous in terms of postoperative cosmesis, it can be improved by making a Pfannielstein incision. This process and the initial experiences of the surgeons are detailed in a previous report [7].

We investigated the amount of experience that a novice surgeon needs to proficiently perform donor nephrectomy. Thus, at the start, 30 cases were required to progress to phase 2 (developmental phase) after phase 1 (novice phase), and an additional 35 cases were required to progress to phase 3 (competency phase). Takagi et al. [8] compared the learning curves of various nephrectomy techniques such as laparoscopic, hand-assisted retroperitoneal, and robotic donor nephrectomies (LDN, HRDN, and RDN, respectively), in a large-scale cohort study that included 1,895 cases. They confirmed that the number of cases required to overcome the learning curve was 45, 23, and 26 for HRDN, LDN, and RDN, respectively. The mean operation time for HRDN was 165 minutes, which was the shortest compared with that of the other techniques (LDN, 184 minutes and RDN, 180 minutes). Postoperative complications of HRDN occurred in 1.4% of patients and did not differ from those of other operative methods; besides, the numbers of complications were not significantly different according to surgical proficiency. They suggested that higher BMI in hand-assisted nephrectomy resulted in a longer learning curve than the other techniques. Zhu et al. [9] analyzed the learning curve of modified hand-assisted donor nephrectomy. They divided the phases according to surgical proficiency using a design similar to that used in the present study. Phase 1 included the initial 32 cases, and phase 2 included the remaining 38 cases. The mean operative time was shorter than that in our study (129.4 minutes). Overall, postoperative complications were higher at 43.8% in phase 1, 26.3% in phase 2, and 29.4% in phase 3. There was one reoperation (3.1%) in phase 1, which was the only grade III complication in all patients. The proportions of grade II or higher complications were 15.6% in phase 1, 13.2% in phase 2, and 3.9% in phase 3. These results are consistent with those of our study in terms of the learning curve and postoperative complications.

Park et al. [10] reported the learning curve of video-assisted mini-laparotomy (VAM) donor nephrectomy through the CUSUM analysis for 50 patients. They suggested that the first significant decrease in the operation time occurred after the 17th case (phase 1) and that the operation time stabilized after the 40th patient (phase 2), leading to a level of proficiency. The operation time was very short: 174.2 minutes in phase 1 and 135.6 minutes in phase 3. They reported that the reason for the short learning curve and operation time was that VAM donor nephrectomy is a hybrid open technique that does not use laparoscopy or robotic instruments and does not require bowel mobilization through a retroperitoneal approach. Martin et al. [11] reported that 37 patients were required to overcome the learning curve in a study of 73 consecutive patients with LDN.

The operation time in our study may have been slightly longer than that reported in other studies. However, this may be due to differences in the approach and surgeons' habits, confirming that a significant and consistent reduction in surgical time is important in learning curve analysis. In addition, while urologists mostly performed the surgery in other studies, a gastrointestinal surgeon performed it in our study. We believe that the overall operation time was slightly extended because of unfamiliarity with the organs and colon mobilization for the peritoneal approach. In phase 3, the operation time was significantly reduced to 160 minutes; considering the results of previous studies, we believe that the phase classification employed in the current study to overcome the learning curve is acceptable.

In general, many studies have analyzed the learning curve in terms of the operation time. This parameter is widely used because it allows the intuitive evaluation of surgical competence. However, because postoperative complications are also an important issue in transplantation, we conducted a risk-adjusted analysis to consider these aspects. In the RA-CUSUM analysis based on the occurrence of complications, phase 1 was identified in 17 cases. Because no related studies were conducted using the RA-CUSUM analysis, a comparison with other studies was difficult. The learning curve of RA-CUSUM was slightly shorter than that of $CUSUM_{OT}$. However, the incidence of postoperative complications was low, and no major complications were greater than grade IIIa, which may have influenced our results. Because of the low incidence and grade of postoperative complications, $Phase_{OT}$ rather than $Phase_{RA}$ was chosen for group comparisons. We believe that well-trained general surgeons may start operating safely without major complications in selected patients. Benavides et al. reported an overall complication rate of 12.5% after HLDN, which is consistent with our results, in which the major complication rate of CDC Grade III or higher was 2.5%. Risk factors related to complications included paramedian incision, history of abdominopelvic surgery, and low surgical experience [12]. In this study, although there were no postoperative complications in phase 3, chyle leaks accounted for more than half of the complications in phases 1 and 2. All chyle leaks occurred in the left nephrectomy and were possibly due to deep dissection around the aorta. As surgical experience increased, excessive dissection was avoided and an appropriate extent of resection was performed; therefore, this complication no longer occurred in phase 3. Caumartin et al. [13] and Aerts et al. [14] reported surgical treatment of chyle leaks after LDN. However, all of our patients were well treated with conservative care, such as stopping feeding or a medium-chain triglyceride diet.

Increased BMI is associated with greater visceral fat accumulation. However, as the kidney is a retroperitoneal organ, BMI does not significantly affect surgical outcomes. There was a significantly weak positive correlation between BMI and operation time in phase 1. During hilum dissection or colon mobilization, high BMI may cause difficulty in identifying precise anatomical planes and can result in frequent minor bleeding. These factors have the potential to prolong the operation time in phase 1. There was no correlation with the operation time in phases 2 and 3, in which surgical proficiency was obtained.

Generally, the right kidney is considered relatively easier to operate on because the adrenal vein, gonadal vein, and lumbar vein branches do not drain into the renal vein. However, the right renal vein is relatively short, which can make vein anastomosis somewhat challenging and raises donor safety issues such as the risk of thromboembolism. Therefore, left nephrectomy has generally been preferred. The operation time based on direction has been reported variably in many studies, so no conclusion has been reached yet. In our study, the operation time based on direction showed a statistically significant difference, with the right nephrectomy at 199.3 minutes and the left nephrectomy at 220.6 minutes ($P = 0.048$). However, there were no significant directional differences between phases. Therefore, we do not believe that the direction had a significant impact on the CUSUM of operation times. Additionally, many studies have reported no differences in donor safety or renal function based on direction.

Swartz et al. [15] reported that the right nephrectomy showed a shorter operation time numerically, but it was not statistically significant. Similarly, Nishida et al. [16] reported no significant differences in operation time or donor safety between right and left nephrectomies. On the other hand, Sawatzky et al. [17] confirmed that right nephrectomy had a shorter operation time with similar postoperative outcomes. In a randomized controlled trial by Minnee et al. [18], the operation time for left donor nephrectomy was significantly shorter, and the surgical outcomes were similar for both sides.

This study has a few limitations. First, selection bias, including the initial experience of a novice surgeon, was inevitable because this was a retrospective cohort study. Therefore, the results from all cohorts cannot be representative of the general donor nephrectomy patient group. However, because of the characteristics of this patient group, the phase classification was relatively clear, and the learning curve analysis and phase-specific results were easy to compare. Second, it may be difficult to extend the results of this study and apply them to all surgeons. Although this study was designed to analyze the learning curve of a surgeon with no experience in nephrectomy, the participating surgeon had already performed more than 600 open and laparoscopic abdominal surgeries when operating on the first case. Because of the high proficiency in manipulating surgical instruments, finding appropriate anatomical planes, and achieving hemostasis have already been obtained, caution should be exercised when directly applying the results of this study to a surgeon who has just completed resident training. Third, because there were no major complications of grade IIIA or higher in any of the cases, various analyses related to complications could not be conducted. However, we confirmed that chyle leaks can occur during left nephrectomy, analyzed their cause, and proved that they can be avoided by improving surgical skills.

Donor safety is the most important issue in transplantation surgery. Our study is the first to analyze the CUSUM for surgical time ($CUSUM_{OT}$) and complication rate (RA-CUSUM). A knowledge of these values allows for the analysis of surgical proficiency and risk in a multifaceted way by considering changes in surgical skill and trends in the occurrence of postoperative complications over the cases.

In conclusion, general surgeons trained in donor nephrectomy can safely perform HLDN based on patient selection. Initially, 30 cases were needed to overcome the learning curve, and a risk-adjusted analysis considering postoperative complications confirmed stabilization in 17 cases.

ACKNOWLEDGEMENTS

We appreciate our clinical research assistant, Yuri Kwak, for her efforts with data collection.

Fund/Grant Support

This work was supported by clinical research grant from Pusan National University Hospital in 2024.

Conflict of Interest

No potential conflict of interest relevant to this article was reported.

ORCID iD

Chang In Choi: https://orcid.org/0000-0002-1920-1879
Kyeong Jun Lee: https://orcid.org/0000-0002-0754-5172
Min Joo Kim: https://orcid.org/0009-0004-4363-3040
Jae-Kyun Park: https://orcid.org/0000-0001-6662-3065
Da Woon Kim: https://orcid.org/0000-0002-9471-5976
Hyo Jin Kim: https://orcid.org/0000-0001-9289-9073
Harin Rhee: https://orcid.org/0000-0001-6257-8551
Sang Heon Song: https://orcid.org/0000-0002-8218-6974
Eun Young Seong: https://orcid.org/0000-0002-6006-0051
Dae-Hwan Kim: https://orcid.org/0000-0002-0045-5692
Tae Yong Jeon: https://orcid.org/0000-0001-7166-3352
Hyuk Jae Jung: https://orcid.org/0000-0003-3407-5855

Author Contribution

Conceptualization: CIC, HJJ, SHS
Formal Analysis: CIC, JKP, DWK, HR
Investigation: MJK, DWK, HJK, HR
Methodology: KJL, CIC, HJJ, JKP, EYS
Project Administration: DHK, TYJ, SHS, EYS
Writing – Original Draft: CIC
Writing – Review & Editing: All authors

REFERENCES

1. Shockcor NM, Sultan S, Alvarez-Casas J, Brazio PS, Phelan M, LaMattina JC, et al. Minimally invasive donor nephrectomy: current state of the art. Langenbecks Arch Surg 2018;403:681-91.
2. Elmaraezy A, Abushouk AI, Kamel M, Negida A, Naser O. Should hand-assisted retroperitoneoscopic nephrectomy replace the standard laparoscopic technique for living donor nephrectomy? A meta-analysis. Int J Surg 2017;40:83-90.
3. Velidedeoglu E, Williams N, Brayman KL, Desai NM, Campos L, Palanjian M, et al. Comparison of open, laparoscopic, and hand-assisted approaches to live-donor nephrectomy. Transplantation 2002;74:169-72.
4. Wohl H. The cusum plot: its utility in the analysis of clinical data. N Engl J Med 1977;296:1044-5.
5. de Leval MR, François K, Bull C, Brawn W, Spiegelhalter D. Analysis of a cluster of surgical failures. Application to a series of neonatal arterial switch operations. J Thorac Cardiovasc Surg 1994;107:914-23.
6. Williams SM, Parry BR, Schlup MM. Quality control: an application of the cusum. BMJ 1992;304:1359-61.
7. Choi CI, Kim DI, Baek SH, Chung YS, Kim DH, Jeon TY, et al. Initial experience with hand-assisted laparoscopic living donor nephrectomy: training and clinical practice as a general surgeon. Transplant Proc 2018;50:3113-20.
8. Takagi K, Kimenai HJ, Terkivatan T, Tran KT, Ijzermans JN, Minnee RC. Learning curves of minimally invasive donor nephrectomy in a high-volume center: a cohort study of 1895 consecutive living donors. Int J Surg 2021;86:7-12.
9. Zhu D, Hong P, Zhu J, Ye X, Chen Y, Fan Y, et al. Cumulative sum analysis of the learning curve for modified retroperitoneoscopic living-donor nephrectomy. Urol Int 2018;101:425-36.
10. Park JS, Ahn HK, Na J, Lee HH, Yoon YE, Yoon MG, et al. Cumulative sum analysis of the learning curve for video-assisted minilaparotomy donor nephrectomy in healthy kidney donors. Medicine (Baltimore) 2018;97:e0560.

11. Martin GL, Guise AI, Bernie JE, Bargman V, Goggins W, Sundaram CP. Laparoscopic donor nephrectomy: effects of learning curve on surgical outcomes. Transplant Proc 2007;39:27-9.
12. Benavides X, Rogers RT, Tan EK, Merzkani MA, Thirunavukkarasu S, Yigitbilek F, et al. Complications after hand-assisted laparoscopic living donor nephrectomy. Mayo Clin Proc 2022;97:894-904.
13. Caumartin Y, Pouliot F, Sabbagh R, Dujardin T. Chylous ascites as a complication of laparoscopic donor nephrectomy. Transpl Int 2005;18:1378-81.
14. Aerts J, Matas A, Sutherland D, Kandaswamy R. Chylous ascites requiring surgical intervention after donor nephrectomy: case series and single center experience. Am J Transplant 2010;10:124-8.
15. Swartz DE, Cho E, Flowers JL, Dunkin BJ, Ramey JR, Bartlett ST, et al. Laparoscopic right donor nephrectomy: technique and comparison with left nephrectomy. Surg Endosc 2001;15:1390-4.
16. Nishida S, Ohyama T, Minamisono K, Sasaki H, Iwami D. Retroperitoneoscopic donor nephrectomy on the right side provides equivalent outcomes and donor safety to that on the left side. Transplant Proc 2023;55:744-7.
17. Sawatzky M, Altaf A, Ellsmere J, Klassen D, Walsh M, Molinari M, et al. Is right laparoscopic donor nephrectomy right? Surg Endosc 2009;23:1321-5.
18. Minnee RC, Bemelman WA, Maartense S, Bemelman FJ, Gouma DJ, Idu MM. Left or right kidney in hand-assisted donor nephrectomy? A randomized controlled trial. Transplantation 2008;85:203-8.