Impact of mentorship on the learning curve of unilateral biportal endoscopic unilateral laminotomy for bilateral decompression in lumbar spinal stenosis: a cumulative sum analysis across 2 generations of surgeons

Shijie Liu, Siyuan Yao, Yao Zhang, Wancheng Lin, Meng Yi, Jipeng Song, Lixiang Ding

Department of Spine Surgery, Beijing Shijitan Hospital, Capital Medical University, Beijing, China

KEY WORDS

learning curve, lumbar spinal stenosis, minimally-invasive, second-generation surgeon, unilateral biportal endoscopy

ABSTRACT

INTRODUCTION Unilateral biportal endoscopic unilateral laminotomy for bilateral decompression (UBE-ULBD) is a minimally-invasive yet technically demanding procedure for lumbar spinal stenosis.

AIM This study aimed to compare the learning curves of 2 generations of surgeons performing UBE-ULBD under a structured mentorship model.

MATERIALS AND METHODS We retrospectively analyzed 200 consecutive surgeries performed between January 2020 and June 2024. The first-generation surgeon (FGS) performed all procedures independently. The second-generation surgeon (SGS) assisted in 30 surgeries and then received on-site supervision for the first 15 independent cases. Data on operative time, blood loss, complications, and clinical outcomes, including the Visual Analog Scale and Oswestry Disability Index, were collected. Operative time–based cumulative sum analysis was used to evaluate the learning curves.

RESULTS The FGS achieved proficiency after 37 and the SGS after 29 procedures. The SGS had significantly shorter mean (SD) operative time of 127.6 (13.2) vs 137.1 (19.3) minutes and lower blood mean (SD) loss of 49 (13.6) vs 57.7 (20.6) milliliters, as compared with his first-generation counterpart. Complications and clinical outcomes were comparable. After achieving proficiency, both surgeons showed improved efficiency without differences in safety or outcomes.

CONCLUSIONS Under the guidance of the FGS, the SGS achieved proficiency in UBE-ULBD more rapidly, as reflected in the shorter operative time. Moreover, once proficiency was reached, no notable differences were observed between the 2 surgeons in terms of postoperative complications or clinical outcomes.

Correspondence to:
Lixiang Ding, MD, PhD, Department of Spine Surgery, Beijing Shijitan Hospital, Capital Medical University, 10 Tieyi Road, Yangfangdian, Haidian District, 100038 Beijing, China, phone: +86 13910912188, email: dinglx@bjsjth.cn
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INTRODUCTION Lumbar spinal stenosis (LSS) is a common degenerative spinal disorder characterized by hypertrophy of the ligamentum flavum and facet joint overgrowth, leading to a reduction in the spinal canal volume and compression of neural structures.[1,2] These pathological lesions result in a spectrum of clinical symptoms, including neurogenic claudication, low back pain, and impaired motor function.[3]

For decades, conventional open laminectomy has been regarded as the gold standard surgical treatment for patients with LSS who fail to respond to systematic conservative therapy.[4,5] Although this procedure can effectively relieve symptoms, it has several drawbacks. Extensive dissection and retraction of the paraspinal soft tissues are required, resulting in significant intraoperative blood loss, considerable postoperative pain, delayed functional recovery, and a potential risk of postoperative chronic low back pain due to spinal instability.[6-8]

To overcome these limitations, spinal surgery has gradually shifted toward minimally-invasive techniques.[9,10] Among them, unilateral biportal endoscopic unilateral laminotomy for bilateral decompression (UBE-ULBD) represents a significant advancement, providing an effective and less invasive option for the treatment of single-level LSS.[11,12] A growing body of evidence has demonstrated that, as compared with open decompression, UBE-ULBD results in lesser soft tissue damage, reduced blood loss, shorter length of hospital stay (LOS), and faster recovery, while providing comparable or even superior clinical outcomes.[13,14] Despite its significant clinical advantages, widespread adoption of UBE-ULBD remains challenging. The procedure demands a high level of technical proficiency while ensuring patient safety, which involves an inherently steep learning curve.

Mastering this newly developed approach has drawn increasing academic attention. However, most previous studies investigating the learning curve of UBE-ULBD have primarily focused on novice surgeons, while overlooking a critical factor, which is the impact of mentorship during surgical training. Therefore, this study retrospectively compared the learning curves of a first-generation surgeon (LD; FGS) and a second-generation surgeon (JS; SGS), trained under the former's supervision, aiming to elucidate the role of mentorship in acquiring proficiency in UBE-ULBD for single-level LSS.

AIM We aimed to quantitatively compare the learning curves of 2 generations of surgeons performing UBE-ULBD, and to evaluate the impact of structured mentorship on surgical proficiency and clinical outcomes.

MATERIALS AND METHODS

Patient selection All single-level UBE-ULBD procedures performed between January 2020 and June 2024 in the Department of Spine Surgery of the Beijing Shijitan Hospital of the Capital Medical University in Beijing, China, were retrospectively reviewed. All enrolled patients had been treated for LSS.

The inclusion criteria comprised: 1) patients with symptoms of single-level LSS, with or without intermittent claudication, confirmed by physical examination and imaging findings; 2) patients whose symptoms did not improve significantly after at least 3 months of systematic conservative treatment; and 3) patients operated on by the FGS or SGS. The exclusion criteria encompassed: 1) patients with multilevel LSS, where the responsible segment could not be clearly identified; 2) imaging evidence of lumbar instability, spondylolisthesis, or degenerative scoliosis; 3) a history of surgery at the operative level; 4) presence of spinal tuberculosis, tumor, or other specific spinal pathologies; and 5) patients with clinical follow-up of less than 12 months, incomplete medical records, or missing key clinical data.

Structured mentorship model Prior to 2020, this procedure had not been carried out in our department. Beginning in 2020, the FGS initiated independent performance of UBE-ULBD following the completion of formal training. The SGS became proficient in the UBE-ULBD technique by assisting the former, and was involved in approximately 30 procedures as an assistant. During these operations, the FGS provided mentorship, while postoperative discussions and video reviews of each surgery were conducted jointly by the 2 surgeons. Subsequently, the SGS began to perform UBE-ULBD independently, although the initial 15 cases were carried out under the direct supervision of the FGS. Both surgeons had substantial prior experience in conventional open procedures: the FGS had performed more than 1000 open lumbar decompressions, and the SGS had carried out over 800. Furthermore, neither had prior experience with UBE-ULBD before the beginning of the study. The entire training process followed a structured mentorship model which consisted of 3 sequential stages: observation and assistance, supervised independent performance, and postoperative debriefing. During the observation and assistance phase, the SGS participated in 30 UBE-ULBD procedures as an assistant. His responsibilities were limited to instrument delivery, without direct surgical manipulation. During this phase, the FGS provided real-time explanations of key operative steps, including establishment of the surgical approach, control of the extent of laminar drilling, exposure and resection of the ligamentum flavum, and contralateral decompression. During the supervised independent practice phase, the SGS began to perform the procedures independently, although the first 15 cases were carried out under direct supervision of the mentor. For key technical steps, including establishment of the biportal approach, laminar drilling, determination of the decompression range, and protection of neural structures, real-time guidance was provided by the FGS, when necessary, to ensure surgical safety. In addition, a standardized postoperative debriefing process was implemented. After each procedure, both surgeons jointly reviewed the surgical recordings and systematically analyzed key technical aspects, including intraoperative visualization management, bleeding control, laminar drilling techniques, identification of anatomical landmarks, and assessment of decompression adequacy. To evaluate the technical proficiency of the SGS, predefined criteria for basic operative competency were established for this study. They included the ability to independently establish a stable biportal system, accurately identify key anatomical structures, perform laminar drilling and decompression under a clear endoscopic visual field, and safely protect neural structures. Only when these key steps could be consistently completed without serious complications was the SGS allowed to gradually transition to a more independent operative stage.

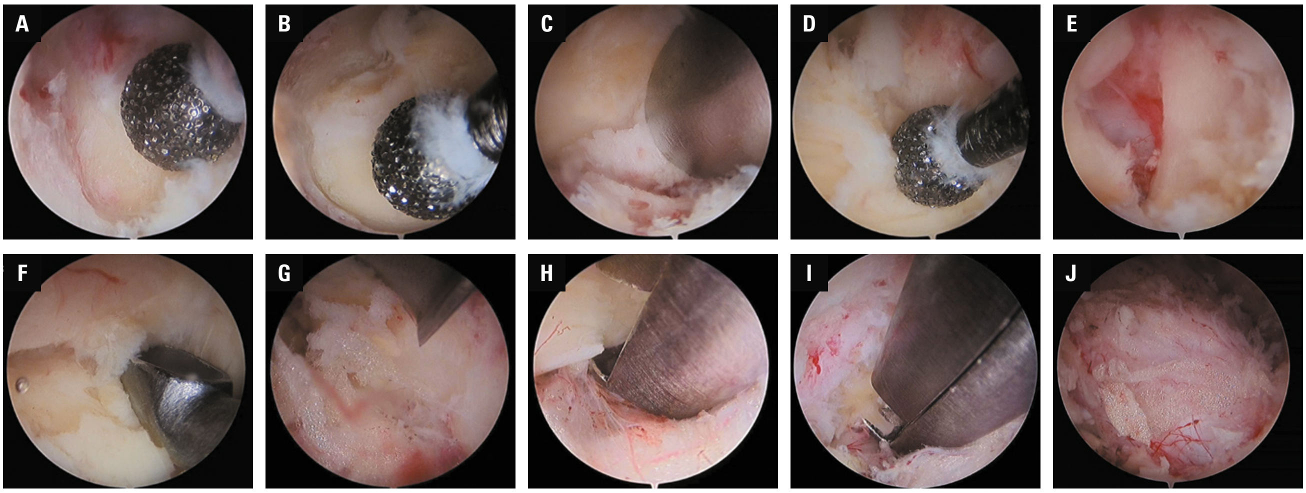

FIGURE 1 Unilateral biportal endoscopic unilateral laminotomy for bilateral decompression; **A** – resection of the inferior margin of the ipsilateral superior lamina; **B** – exposure of the origin of the ligamentum flavum on the ventral side of the superior lamina; **C** – resection of the medial portion of the ipsilateral inferior articular process; **D** – resection of the superior margin of the ipsilateral inferior lamina; **E** – exposure and resection of the ipsilateral ligamentum flavum from its origin to insertion; **F** – dissection of the ventral attachment of the ligamentum flavum to the inferior margin of the contralateral superior lamina; **G** – resection of the superior margin of the contralateral inferior lamina; **H** – resection of the contralateral ligamentum flavum; **I** – resection of the contralateral superior articular process; **J** – good dural sac pulsation

Surgical technique The patient was placed in the prone position under general anesthesia, with a U-shaped soft cushion placed under the abdomen to enlarge the interlaminar space. After C-arm fluoroscopic localization, the midline, target intervertebral space, and pedicle projections were marked on the skin surface. Skin incisions were then marked above and below the intervertebral space along the medial border of the ipsilateral pedicle. The skin and fascia were incised sequentially, and the paraspinal muscles were bluntly dissected to the target bony landmarks using serial dilators. After fluoroscopic confirmation of the position, working cannulas were inserted to establish the surgical portals. A 30 ° endoscope was inserted through the viewing portal, and, under continuous saline irrigation, a radiofrequency probe was used to carefully clear the soft tissue from the intervertebral space, gradually exposing the bony landmarks, including the inferior edge of the superior lamina, the base of the spinous process, the facet joints, and the superior edge of the inferior lamina. Part of the lamina was removed using a high-speed drill combined with Kerrison rongeurs to expose the cephalad attachment of the ligamentum flavum. The ipsilateral ligamentum flavum was then excised. Partial resection of the facet joint and subclinical bone drilling were performed until the medial wall of the ipsilateral pedicle was fully exposed, ensuring adequate decompression of the ipsilateral nerve root. Drilling was continued at the base of the spinous process and the ipsilateral lamina. Using the "over-the-top" technique, the contralateral lamina and ligamentum flavum were gradually removed, terminating at the medial wall of the contralateral pedicle, achieving complete bilateral nerve decompression. After confirming thorough decompression and good dural pulsation, meticulous hemostasis was performed with a radiofrequency probe. The working cannulas were removed, the incision was closed in layers, and a drainage tube was placed (**FIGURE 1**).

Data collection and analysis We systematically collected baseline data of all patients, including age, sex, body mass index, medical history, operative level, and smoking status. Surgical parameters, including operative time, estimated blood loss, and complications, were also recorded. Functional status and the severity of back and leg pain were assessed using the Oswestry Disability Index (ODI) and Visual Analog Scale (VAS), respectively, preoperatively, on postoperative day 3, and at final follow-up.

The cumulative sum (CUSUM) method was used to evaluate the learning curve based on operative time. The CUSUM was calculated using the following formula:

$$\mathrm{CUSUM} = \sum_{\mathrm{i}=1}^{\mathrm{n}} (\mathrm{Xi} - \mathrm{U})$$

where Xi represents the operative time of each case, U is the mean operative time of all cases, and n is the sequential case number according to operative time. Scatter plots of the CUSUM analysis were generated using GraphPad Prism software, version 10.0 (GraphPad Software, San Diego, California, United States), and curve fitting was performed to obtain the fitted function. The coefficient of determination R^2 was used to assess the goodness of fit, with values closer to 1 indicating better fit. The model with the highest R^2 was selected as the optimal fit. The first derivative of the fitted curve was calculated, and the peak point determined based on

TABLE 1 Demographic characteristics of the study population

Parameter		First-generation surgeon group (n = 110)	Second-generation surgeon group (n = 90)	*P* value
Age, y		65.7 (7.5)	66.6 (7.9)	0.38
Men		49 (44.5)	48 (53.3)	0.22
Body mass index, kg/m^2		26.1 (2.9)	25.7 (1.9)	0.36
Comorbidities	Hypertension	45 (40.9)	33 (36.7)	0.54
	Diabetes	41 (37.3)	35 (38.9)	0.82
Current smoker		22 (20)	17 (18.9)	0.84
Operative level	L3/L4	29 (26.4)	17 (18.9)	0.45
	L4/L5	64 (58.2)	57 (63.3)	
	L5/S1	17 (15.5)	16 (16.5)	

Data are presented as number (percentage) or mean (SD).

TABLE 2 Surgical-related parameters of the patients treated by the first- and second-generation surgeons

Parameter	First-generation surgeon group (n = 110)	Second-generation surgeon group (n = 90)	*P* value
Operative time, min	137.1 (19.3)	127.6 (13.2)	<0.001
Estimated blood loss, ml	57.7 (20.6)	49 (13.6)	<0.001
Length of hospital stay, d	3.6 (1.5)	3.6 (1.6)	0.79
Facet preservation rate	82.8 (7)	84.3 (5.8)	0.11
Total complication rate	10 (9.1)	7 (7.8)	0.74

Data are presented as number (percentage) or mean (SD).

TABLE 3 Clinical outcomes of the study participants

Parameter		First-generation surgeon group (n = 110)	Second-generation surgeon group (n = 90)	*P* value[a]
VAS back pain score, points	Preoperative	7.2 (1)	7.4 (1.1)	0.19
	3 days after surgery	3.2 (1)	3.1 (1.1)	0.3
	Last follow-up	1.7 (1)	1.7 (1)	0.88
	P value[b]	<0.001	<0.001	–
VAS leg pain score, points	Preoperative	7.2 (0.8)	7.2 (1)	0.86
	3 days after surgery	3.1 (1)	3.2 (1.1)	0.22
	Last follow-up	1.7 (0.9)	1.8 (1)	0.31
	P value[b]	<0.001	<0.001	–
ODI score, points	Preoperative	59.9 (8.3)	60 (9.7)	0.93
	3 days after surgery	29.6 (4.3)	30.2 (4.2)	0.36
	Last follow-up	14.9 (3.8)	13.9 (3.5)	0.07
	P value[b]	<0.001	<0.001	–

Data are presented as mean (SD).

a Independent-samples *t* test (comparisons between the groups)

b Repeated-measures analysis of variance

Abbreviations: ODI, Oswestry Disability Index; VAS, Visual Analog Scale

the slope values was used to delineate the phases of the learning curve.

Statistical analysis All statistical analyses were performed using SPSS Statistics software, version 25.0 (IBM Corp., Armonk, New York, United States). Numerical variables were first evaluated for normal distribution and homogeneity of variance. Continuous variables were expressed as mean (SD) and compared between the groups using the independent-samples *t* test. Categorical variables were presented as frequencies and percentages, and compared using the χ^2 test or the Fisher exact test. Changes in clinical outcomes across the 3 time points were assessed using the repeated-measures analysis of variance. All statistical tests were 2-sided, with a *P* value below 0.05 considered significant.

Ethics This retrospective study was approved by the Ethics Committee of the Beijing Shijitan Hospital of the Capital Medical University

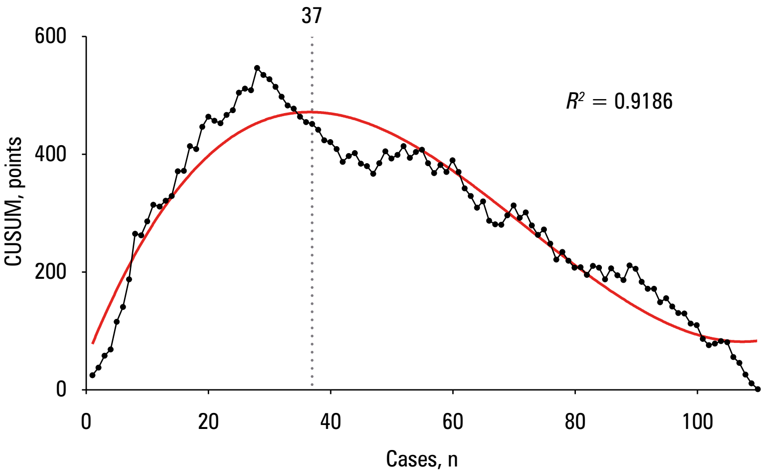

FIGURE 2 Cumulative sum (CUSUM) chart of operative time in the first-generation surgeon group

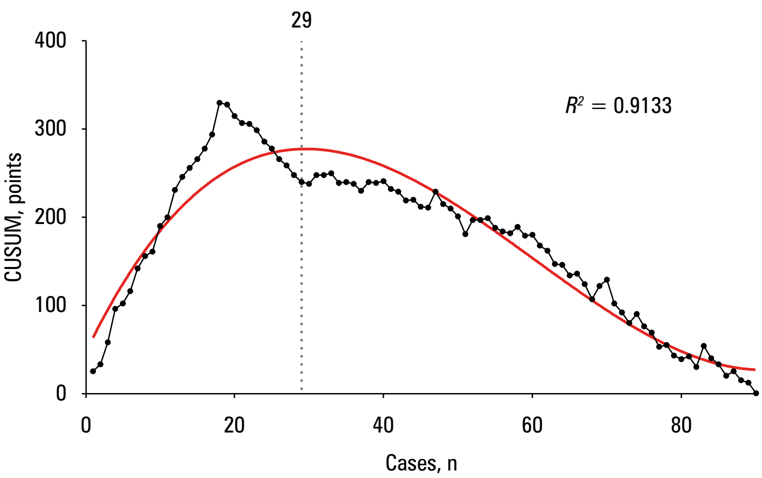

FIGURE 3 Cumulative sum (CUSUM) chart of operative time in the second-generation surgeon group

(IIT2024-032-003), and was conducted in accordance with the Declaration of Helsinki. Written informed consent was obtained from all participants.

RESULTS Between January 2020 and June 2024, the FGS and SGS performed 110 and 90 UBE-ULBD procedures, respectively. In the FGS group, 49 patients (44.5%) were men, as compared with 48 individuals (53.3%) in the SGS group. No significant differences were observed between the groups in terms of demographic variables (**TABLE 1**).

Mean (SD) operative times for the FGS and SGS groups were 137.1 (19.3) and 127.6 (13.2) minutes, respectively (P <0.001). Mean (SD) estimated blood loss was 57.7 (20.6) ml in the FGS group and 49 (13.6) ml in the SGS cohort (P <0.001). There were no significant differences between the groups in terms of LOS, facet preservation rates, and overall complication rates (**TABLE 2**).

Postoperative complications occurred in 10 patients in the FGS group, including 6 dural tears, 4 cases of transient lower limb pain or numbness, and 1 case of residual symptoms due to insufficient decompression. In the SGS group, 7 complications were recorded: 4 dural tears and 3 cases of transient lower limb pain or numbness. All dural tears were repaired intraoperatively using absorbable dural patches, and no related postoperative symptoms were observed. The patients with transient lower limb pain or numbness experienced improvement after conservative treatment. The individual with insufficient decompression showed no symptom relief after 2 months of conservative management, and subsequently underwent posterior lumbar interbody fusion at the same level, which led to symptom resolution.

Regarding clinical outcomes, intergroup comparisons showed no differences in the VAS or ODI scores between the groups at any time point. However, intragroup analyses showed improvements in both scores at the final follow-up, as compared with the preoperative values in each cohort (P <0.001; **TABLE 3**).

Postoperatively, both groups showed marked improvements in back and leg pain VAS and ODI scores, in comparison with the preoperative values (P <0.001). However, no significant differences were observed between the cohorts at any of the 3 time points (preoperatively, on postoperative day 3, and at the final follow-up) for either VAS or ODI scores (**TABLE 3**).

The CUSUM method based on operative time was applied to generate scatter plots and fit the learning curves (**FIGURES 2** and **3**). For both groups, the cubic polynomial model was identified as the optimal fit. The fitted function for the FGS group was: $CUSUM = 51.55 + 25.91 \times n - 0.4744 \times n^2 + 0.002195 \times n^3$, and for the SGS group, it was: $CUSUM = 45.94 + 17.57 \times n - 0.3935 \times n^2 + 0.002177 \times n^3$.

The results showed that, in the FGS group, the slope of the curve changed from positive to negative at case 37. Accordingly, the 110 cases were divided into the learning phase (cases 1–37) and the mastery phase (cases 38–110). The comparison of demographic characteristics between the 2 stages is presented in **TABLE 4**. Mean (SD) operative time during the learning phase was longer than that during the mastery phase (149.7 [22] vs 130.7 [13.9] min; P <0.001), and the estimated intraoperative blood loss was also greater during this stage (P <0.001). Furthermore, facet preservation in the learning phase was lower than that in the proficiency phase (80% vs 84.2%; P = 0.003). No significant differences were observed between the 2 stages in terms of LOS or total complication rates (**TABLE 5**). With respect to clinical outcomes, both phases demonstrated improvements in VAS and ODI scores at the final follow-up, as compared with the preoperative values (P <0.001). However, no significant differences were found between the 2 stages at any follow-up time point (**TABLE 6**).

In the SGS group, the slope of the curve changed from positive to negative at case 29.

TABLE 4 Demographic characteristics of the patients before and after the learning curve milestone of the first- and second-generation surgeons

Parameter		First-generation surgeon group (n = 110)			Second-generation surgeon group (n = 90)		
		Learning phase (n = 37)	Mastery phase (n = 73)	*P* value	Learning phase (n = 29)	Mastery phase (n = 61)	*P* value
Age, y		65.4 (8.2)	65.8 (7.1)	0.82	64.7 (7)	67.5 (8.2)	0.11
Men		17 (45.9)	32 (43.8)	0.83	15 (51.7)	33 (54.1)	0.83
Body mass index, kg/m²		26.7 (3.2)	25.7 (2.6)	0.08	25.6 (2)	25.8 (1.8)	0.66
Comorbidities	Hypertension	14 (37.8)	31 (42.5)	0.64	13 (44.8)	20 (32.8)	0.27
	Diabetes	17 (45.9)	24 (32.9)	0.18	9 (31)	26 (42.6)	0.29
Current smoker		9 (24.3)	13 (17.8)	0.42	8 (27.6)	9 (14.8)	0.15
Operative level	L3/L4	7 (18.9)	22 (30.1)	0.34	3 (10.3)	12 (19.7)	0.51
	L4/L5	25 (67.6)	39 (53.4)		21 (72.4)	38 (62.3)	
	L5/S1	5 (13.5)	12 (16.4)		5 (17.2)	11 (18)	

Data are presented as number (percentage) or mean (SD).

TABLE 5 Surgical-related parameters of the patients before and after the learning curve milestone of the first- and second-generation surgeons

Parameter	First-generation surgeon group (n = 110)			Second-generation surgeon group (n = 90)		
	Learning phase (n = 37)	Mastery phase (n = 73)	*P* value	Learning phase (n = 37)	Mastery phase (n = 73)	*P* value
Operative time, min	149.7 (22.2)	130.7 (13.9)	<0.001	135.9 (15.5)	123.7 (9.8)	<0.001
Estimated blood loss, ml	67.8 (26.2)	52.5 (14.7)	<0.001	56.21 (15.7)	45.5 (11)	<0.001
Length of hospital stay, d	3.8 (1.5)	3.5 (1.5)	0.28	3.9 (1.8)	3.5 (1.4)	0.25
Facet preservation rate	80 (8.6)	84.2 (5.7)	0.003	83.3 (7.8)	84.8 (4.5)	0.25
Total complication rate	4 (10.8)	6 (8.2)	0.66	3 (10.3)	4 (6.6)	0.53

Data are presented as number (percentage) or mean (SD).

Accordingly, the 90 patients were divided into the learning phase (cases 1–29) and the mastery phase (cases 30–90). Patient demographics are detailed in **TABLE 4**. Mean (SD) operative time was longer in the learning phase than the mastery phase (135.9 [15.5] vs 123.7 [9.8] min; $P < 0.001$), accompanied by greater estimated blood loss ($P < 0.001$). No significant differences were observed between the 2 stages regarding LOS, facet preservation, and overall complication rates (**TABLE 5**). In terms of clinical outcomes, both phases showed considerable improvements in VAS and ODI scores at the final follow-up, in comparison with the preoperative values ($P < 0.001$). However, no significant differences were observed between the 2 stages (**TABLE 6**).

DISCUSSION Our study was the first to utilize the CUSUM analysis to quantitatively compare the learning curves of 2 generations of surgeons mastering the UBE-ULBD technique. The results demonstrated that the learning curve of SGSs could be shortened under the guidance of first-generation mentors (29 vs 37 cases), without a significant increase in adverse clinical outcomes or the total incidence of postoperative complications.

In recent years, UBE has attracted increasing attention owing to its minimally-invasive advantages in the treatment of LSS. Although early studies reported inconsistent results regarding the efficacy of UBE-ULBD, more recent evidence has demonstrated that this technique achieves clinical outcomes comparable to those of conventional open surgery, while offering distinct advantages, such as reduced intraoperative tissue trauma and faster postoperative recovery.[11,13,15] The core feature of the UBE technique lies in its use of separate working and viewing portals to establish the surgical approach. This dual-channel design provides greater maneuverability and freedom for surgical instruments, allowing for adequate neural decompression while preserving the bony structures of the spine more effectively.[16,17] Previous studies have reported that the ipsilateral facet joint preservation rate during UBE-ULBD can reach approximately 89%, resulting in a lesser impact on lumbar stability and a significantly reduced risk of postoperative spinal instability.[18,19]

As an emerging endoscopic technique, UBE-ULBD requires surgeons to undergo a period of training before achieving proficiency. The learning curve intuitively reflects how quickly a specific surgical skill is mastered, and is usually defined by the number of cases required to reach competence.[20] CUSUM analysis is a mean-based statistical method that has been increasingly applied in the surgical field in recent years to objectively and reliably identify the inflection point of a surgeon's learning curve. This approach enables the evaluation of changes in surgical proficiency over time.[21,22]

In this study, the FGS required 37 cases to achieve proficiency in performing UBE-ULBD,

TABLE 6 Clinical outcomes of the patients before and after the learning curve milestone of the first- and second-generation surgeons

Parameter		First-generation surgeon group (n = 110)			Second-generation surgeon group (n = 90)		
		Learning phase (n = 37)	Mastery phase (n = 73)	*P* value	Learning phase (n = 29)	Mastery phase (n = 61)	*P* value[a]
VAS back pain score, points	Preoperative	7.1 (1.1)	7.3 (1)	0.52	7.3 (1.2)	7.5 (1.1)	0.56
	3 days after surgery	3.1 (0.9)	3.2 (1)	0.63	2.9 (0.9)	3.1 (1)	0.41
	Last follow-up	1.5 (0.8)	1.7 (1.1)	0.33	1.8 (0.7)	1.6 (1.1)	0.56
	P value[b]	<0.001	<0.001	–	<0.001	<0001	–
VAS leg pain score, points	Preoperative	7.1 (0.7)	7.2 (0.8)	0.54	7.1 (1.1)	7.3 (1)	0.6
	3 days after surgery	3 (1)	3.1 (0.9)	0.57	3.3 (0.9)	3.2 (1.2)	0.47
	Last follow-up	1.6 (0.8)	1.7 (1)	0.58	1.7 (1.1)	1.9 (1)	0.5
	P value[b]	<0.001	<0.001	–	<0.001	<0.001	–
ODI score, points	Preoperative	59.2 (7.5)	60.2 (8.6)	0.59	61.2 (10.2)	59.2 (9.4)	0.29
	3 days after surgery	29.1 (4.7)	29.8 (4.1)	0.43	29.5 (4.3)	30.5 (4.1)	0.27
	Last follow-up	14.1 (3.8)	15.2 (3.7)	0.15	14.7 (3.6)	13.5 (3.4)	0.15
	P value[b]	<0.001	<0.001	–	<0.001	<0.001	–

Data are presented as mean (SD).

a Independent-samples *t* test (comparisons between the groups)

b Repeated-measures analysis of variance

Abbreviations: see **TABLE 3**

which is consistent with previous findings. Earlier studies have reported that approximately 24 to 54 cases were needed for surgeons to become proficient in this technique.[23-25] Of note, in previous research, surgeons performing the procedures rarely had the opportunity to operate under direct, hands-on guidance from experienced colleagues. Alberici et al[26] and Shibasaki et al[27] introduced the concept of the SGS, suggesting that direct mentorship from experienced instructors can significantly shorten the learning curve and reduce operative time. The findings of this study also indicate that, under the professional guidance provided by the FGS, the learning curve for mastering UBE-ULBD technique was substantially shortened for the SGS (29 vs 37 cases). Additionally, mean operative time was shorter (127.6 vs 137.1 min), and the estimated intraoperative blood loss was lower in this group (49 vs 57.7 ml).

Furthermore, regarding the radiological outcomes, our study demonstrated a marked improvement in the ipsilateral facet joint preservation rate for the FGS, as he transitioned from the learning to the mastery phase (80% vs 84.2%; $P = 0.003$). In contrast, for the SGS, no significant difference was observed between the 2 stages. We attribute this early proficiency to the effective guidance provided by the mentor. Under direct supervision, the SGS was able to grasp the critical technical nuances of bone preservation during the initial learning phase, thereby maintaining a consistently high and stable preservation rate from the outset.

Although operative time is an important indicator for evaluating a surgeon's proficiency in a specific surgical technique, surgical safety should also be taken into consideration when assessing learning curves. Therefore, postoperative complications are also regarded as an important indicator for measuring surgical proficiency. Guo et al[28] constructed a risk-adjusted CUSUM (RA-CUSUM) model based on postoperative complications, and their results indicated that surgeons were required to complete at least 41 cases to fully master the technique. In addition, Gulec et al[29] incorporated intraoperative neuromonitoring parameters into the RA-CUSUM analysis, and reported that technical proficiency could be achieved after approximately 16 cases. Meanwhile, Xu et al[23] found that, according to the RA-CUSUM analysis, at least 89 cases were required to achieve a stable surgical success rate. The discrepancies among these studies may be related to differences in patient disease severity and case complexity across centers.[30-32] However, as the overall complication rate in the present study was low, the RA-CUSUM analysis based on complication events was not further performed.

The early and significant inflection point of the learning curve, substantial reductions in operative time and intraoperative blood loss, and early acquisition of bone preservation skills collectively highlight the core value of the FGS in the transmission of experience. This value lies in the systematic transformation of accumulated surgical expertise into structured knowledge that can be efficiently understood and mastered by SGSs. Based on surgical experience, the FGS developed a standardized operative workflow. This process encompassed key technical steps, including rapid establishment of stable dual channels, maintenance of a clear surgical field under continuous irrigation, and safe decompression, which significantly accelerated the SGS's achievement of mastery in the UBE-ULBD procedure. Notably, although no significant differences were observed between the 2 groups regarding overall complication rates and clinical outcomes, the contribution of the guidance provided by the FGS remains of considerable importance. For instance, dural tear is one of the most common complications of UBE-ULBD, and its risk increases markedly when novice surgeons encounter complex cases or prolonged operative times.[33,34] Under the supervision of the mentor, the SGS was able to acquire the key technical skills for preventing and managing dural tears more rapidly, thereby markedly enhancing the safety of his early-stage procedures.

Inaccurate assessment of the decompression range is a common reason for performing inadequate decompression by novice surgeons.[35,36] Through intraoperative instruction and postoperative debriefing provided by the FGS, the SGS was able to establish accurate judgment criteria at an early stage, thereby effectively avoiding procedure-related complications. This guided training model not only improved the surgical success rate of the SGS but also reduced the need for reoperations, resulting in significant economic benefits for the patients. Moreover, from the perspective of the cost-benefit ratio, although continuous hands-on guidance from first-generation experts inevitably consumes additional medical resources during the initial phase, such as extending individual operative times and requiring the presence of senior surgeons, this structured teaching model significantly shortens the learning curve for SGSs. More importantly, it effectively prevents severe complications that novice surgeons might trigger during their exploratory phase, such as dural tears or revision surgeries caused by inadequate decompression, thereby avoiding the high additional treatment costs associated with these events. Therefore, in the long run, the improvements in clinical safety and the overall conservation of medical resources brought about by mentorship training likely far outweigh early investments in teaching costs.

Limitations This study has several limitations. First, it has a single-center retrospective design with a limited sample size, which may restrict the generalizability of the findings in clinical practice. Further validation is warranted through future multicenter prospective studies with larger cohorts. Second, postoperative outcomes primarily relied on patient-reported functional scores, lacking objective quantitative imaging indicators. Subsequent studies should incorporate postoperative imaging assessments and intraoperative neurophysiological monitoring, combined with long-term patient-reported outcome measures, to achieve a multidimensional evaluation of efficacy. Third, due to the relatively low incidence of postoperative complications in this cohort, the learning curve was assessed solely based on operative time, which may not comprehensively reflect overall surgical proficiency. Future research should explore more objective and comprehensive standards for evaluating surgical competence. Finally, a potential case selection bias exists, as we did not perform quantitative stratification or propensity score matching for baseline case complexity. Since surgeons naturally select simpler cases during their initial learning phase, this lack of matching might have overestimated the mentorship effect. Future analyses should incorporate standardized complexity grading and matched cohorts.

CONCLUSIONS This study employed the CUSUM analysis based on operative time to systematically evaluate the learning curves of 2 generations of surgeons performing the UBE-ULBD procedure. The results demonstrated that both achieved favorable clinical outcomes with a low overall complication rate. Under the guidance of the FGS, the SGS acquired proficiency in UBE-ULBD more rapidly, with shorter mean operative time and less estimated intraoperative blood loss. These findings suggest that, based on our single-center experience, a standardized, experience-driven teaching framework can accelerate skill transfer and potentially enhance the overall quality and safety of early-stage endoscopic spine surgery. However, further multicenter, prospective studies are warranted to validate and generalize these findings.

ARTICLE INFORMATION

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JOURNAL INFORMATION

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