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Research Article

Mastering Minimally Invasive Spine Surgery: Analyzing the Learning Curve, Safety Insights, and Complication Rates in Modern Spinal Procedures

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ABSTRACT

Background: Minimally invasive spine surgery (MISS) is a technique that minimizes tissue trauma and has a quicker recovery period, but it can be quite technically demanding. Operative efficiency and patient safety could be affected by the learning curve.

Objective: To assess the learning curve, perioperative outcomes, and complication rates of MISS.

Methods: A retrospective analytical cohort study with 154 consecutive adult patients who underwent MISS in a tertiary-care hospital was performed. Demographic, clinical, operative, and postoperative data were obtained. Patients were divided into groups based on the number of years they had performed the surgery. Assessed were duration of operation, blood loss, hospitalization, conversion to open surgery, and complications. The proficiency threshold was determined by using a CUSUM analysis, and logistic regression was performed to determine factors associated with complications.

Results: Mean age was 48.6 ± 11.7 years, and 59.1% were male. Operative duration decreased from 123.4 ± 39.6 to 86.7 ± 27.8 minutes, while blood loss decreased from 112.6 ± 64.1 to 69.5 ± 41.7 mL between early and proficiency phases (both $p<0.001$). Complications decreased from 18.2% to 6.5% ($p=0.028$). The proficiency was detected using CUSUM analysis at about 66-70 cases. Complications were independently associated with early case surgery ($p=0.014$).

Conclusion: MISS showed a significant learning curve, showing progressive improvements in working efficiently and safely as the experience increased.

Keywords: Minimally Invasive Spine Surgery, Learning Curve, Complications, Surgical Proficiency, Cusum Analysis.

INTRODUCTION

A major and increasing cause of pain, disability, functional limitation and loss of productivity worldwide, spinal disorders are a major cause of disability.[1] Low back pain (LBP) alone accounted for around 619 million people affected in the world in 2020 and is expected to increase to 843 million by 2050, mainly due to population growth and ageing.[2] There are around 1.71 billion people with musculoskeletal conditions, and LBP is the most prevalent cause of disability in the world.[3] This added demand has been accompanied by the ageing population and higher expectations for quick recovery from functional disability, creating a high need for effective surgical options with fewer disruptive effects.

Conventional open spinal surgery may be adequate to relieve neural compression and achieve stabilization, but often involves a large amount of paraspinal muscle dissection, more soft tissue disruption, and longer recovery.[4-6] Minimally invasive spine surgery (MISS) is an important development in the evolution of the surgical practice of spine surgery, which employs smaller incisions, tubular or endoscopic corridors, microscopic visualization, fluoroscopic assistance, computer-assisted navigation, and increasingly sophisticated instrumentation.[7] Minimally invasive transforaminal lumbar interbody fusion (MIS-

TLIF), endoscopic discectomy, tubular decompression, unilateral biportal endoscopy, and endoscopic lumbar fusion may allow for less tissue damage, less blood loss, and quicker mobilization and hospital discharge when the procedure is performed using these techniques.[8] Improvements in navigation, intraoperative imaging, endoscopy, and special instrumentation have also increased the number of spinal procedures that can be performed via these minimally invasive methods.

Although these benefits can be seen, MISS is also technically challenging and offers a unique learning curve.[9] Early procedures often are difficult because of limited visualization, restricted working corridors, and changed three-dimensional orientation, loss of tactile feedback, and reliance on fluoroscopic and/or endoscopic imaging.[10] Surgical skills are not merely about performing several surgical procedures; it involves improvements in the efficiency of the surgery, amount of blood loss, radiation exposure, conversion to open surgery, post-surgery recovery, and crucially patient safety.[11]

In this context, a systematic analysis of the learning curve of MISS is an opportunity to identify the transition from early technical acquisition to a steady learning curve in terms of surgical expertise, as well as to understand if the improvement in experience is associated with a measurable reduction in complications. This information can be used to guide structured training, mentoring, credentialing, patient selection, and institutional safety standards, and safeguarding patients during the initiation of a technically challenging procedure. The aim of the present study was, therefore, to examine the learning curve of minimally invasive spinal procedures, to investigate whether there was a relationship between the number of surgeries performed and the outcomes during the perioperative period, and to determine the frequency and pattern of complications occurring at various stages of the surgeon's experience. The primary goal of the study was to assess differences in efficiency and safety parameters during the operation and to determine the approximate case limit for the stabilization of proficiency and complication.

METHODS

A retrospective analytical cohort study was performed to assess the learning curve, perioperative safety, and complication rates of minimally invasive spine surgery (MISS). The study was conducted in the Department of Orthopedics Surgery. The study covered a period of six months, from October, 2025 to March, 2026.

The calculated sample size (with OpenEpi version 3.01 at two-proportion comparison) was 140 patients. The statistical power for the present study was set at 80% and the 2-sided confidence level at 95%, assuming a complication rate of about 15% in the early learning phase and 5% in the later proficiency phase. During data verification, incomplete medical records and the absence of some operative variables and exclusions were compensated for by allowing for 10% more, bringing the final target sample size to about 154 patients. All eligible cases were included to enhance the precision of the learning-curve analysis, because more than one procedure was eligible for consecutive procedures during the study period.

A consecutive sampling technique was used. Adult patients ≥18 years with complete perioperative records of eligible minimally invasive spinal procedures (MIPS) (lumbar decompression, endoscopic discectomy, tubular decompression, and minimally invasive fusion) were included. Patients with incomplete surgical and/or postoperative records, patients undergoing conventional open surgery, selected revision surgery, major trauma surgery, spinal tumor surgery, spinal infection surgery, and complex deformity surgery were excluded. Any procedures performed as open surgery were kept for safety analysis and documented as a learning curve outcome.

Data were gathered with a structured data-extraction proforma which was specially prepared for the study. The operative theatre register and electronic medical-record system were first checked to determine the number of patients that might have met the criteria. Then the demographic, clinical, operative and postoperative data for each of the patients was retrieved from the medical record. Demographic factors were age and sex, and clinical factors were BMI, presenting diagnosis, symptom duration, presence of relevant comorbidities, prior spinal surgery, and American Society of Anesthesiologists (ASA) physical status classification as available.[12]

Operative factors were the type of minimally invasive procedure, level of spine performed, surgical indication, chronological case number, operative time, estimated blood loss, intraoperative fluoroscopy/navigation, hospital stay, and conversion to open surgery. The primary exposure variable was the chronological case number, and these were used as surrogates for increasing surgical experience. Cases were also subdivided into sequential categories, as early, intermediate, and proficiency phases, based on the distribution of the total operative experience, for learning-curve analysis.

Postoperative follow-up data were obtained from hospital records and follow-up documentation. These included neurological deficit, incidental durotomy, cerebrospinal fluid leakage, wound infection, postoperative hematoma, nerve root injury, inadequate decompression, implant malposition, postoperative infection, readmission, reoperation, and conversion to open surgery. The overall complication rate was defined as the number of patients who had at least one documented perioperative complication divided by the total number of patients. Major complications were considered those requiring further intervention, reoperation, extended hospitalization, or resulting in a significant systemic or neurological morbidity. Any minor complications were recorded as separate complications. Operative efficiency was evaluated on the basis of operative duration and estimated blood loss, and safety was evaluated on the basis of the number and severity of perioperative complications.

Data were entered, cleaned, coded, and analyzed with software IBM SPSS Statistics version 26.0. Continuous variables were checked for distribution by visual inspection of histograms and Q-Q plots as well as the Shapiro–Wilk test. Data for continuous variables were reported as mean ± SD and for non-normally distributed variables as median (IQR). Frequencies and percentages were used to present categorical variables. The independent-samples t-test was used for comparison between early and later phases of the learning curve for normally distributed continuous variables, while the Mann–Whitney U test was used for non-normally distributed continuous variables. One-way analysis of variance (ANOVA) was used to make comparisons between more than two sequential experience groups. Categorical variables, such as neurologic complication rate, durotomy, infection, conversion to open surgery, and reoperation rates, were compared with the chi-square test or Fisher's exact test.

Pearson's correlation was used to measure the correlation between the case number and the continuous results of the operation, such as the duration of the operation or the amount of blood loss, and, if the assumption of parametric correlation was not met, Spearman's rank correlation was used. Learning curve analysis was also performed by plotting the operative time and complication rates against a running series of cases. Where there were enough observations to conduct a cumulative-sum (CUSUM) analysis, this was done to identify the approximate transition point between the learning and proficiency phases.

Multivariable binary logistic regression was performed to determine factors independently associated with postoperative complications. Variables that were clinically relevant and/or had a p-value <0.20 on univariable analysis were considered for further inclusion in the multivariable model. Confounders that were considered were age, sex, body mass index, comorbidities, type of procedure, operative spinal level, and chronological order of cases. Adjusted odds ratios (AORs) and 95% confidence intervals (CIs) were provided. Multicollinearity was checked before construction of the final regression model. The goodness-of-fit test of Hosmer–Lemeshow was used to determine model fit. All statistical tests were two-tailed, and a p-value <0.05 was considered statistically significant. A 95% confidence interval was used wherever applicable. Data missingness was evaluated before analysis, and variables with missing documentation were not assumed but rather excluded from the analysis.

RESULTS

A total of 154 patients were included in the analysis. Mean age was 48.6 ± 11.7 years, with there being a greater male than female population. Lumbar disc herniation was the most common surgical indication, and most patients were ASA II. Demographic and clinical data for baseline are summarized in Table 1.

A significant improvement in operative efficiency and postoperative recovery was found with experience of surgery, as shown in the comparison between the early and proficiency phases. Higher overall complications were also associated with the early phase (Table 2).

Patients classified by experience into early, intermediate, and proficiency phases had a progressive downward trend in complications. Differences in individual complications did not follow a consistent pattern, and incidental durotomy was recorded in 100 cases. (Table 3)

There were significant improvements in the three case-number groups for the duration of the operation, the amount of blood loss, and the length of hospital stay as shown by sequential analysis. As the procedures progressed, the incidence of complications also gradually decreased (Table 4).

Inverse correlation of chronological case number with each of the following variables (operative duration, estimated blood loss, hospital days, total occurrence of complications) suggests that the surgical work efficiency and safety are becoming better in each successive case number (Table 5).

The CUSUM analysis showed a significant amount of performance variation at the beginning of the learning phase, with increasing stabilization in the learning phase. The transition to relatively stable proficiency took place at about the 66th to 70th case, and thereafter, there were relatively stable levels of operative performance and complication rates (Table 6).

In multivariable logistic regression, lower surgical experience correlated with postoperative complications independent of the other demographic, clinical, and operative factors. Complex or multilevel procedures and longer operative duration also demonstrated associations with increased odds, as seen in the univariable analysis, that were dampened in the multivariable analysis. The final model had satisfactory calibration (Table 7).

Table 1. Demographic and Baseline Clinical Characteristics of the Study Population (N=154)

Variable	Frequency (%) / Mean ± SD
Age, years	48.6 ± 11.7
Age ≥50 years	79 (51.3%)
Male sex	91 (59.1%)
Female sex	63 (40.9%)
BMI, kg/m²	26.1 ± 3.8
BMI ≥25 kg/m²	97 (63.0%)
Symptom duration, months, median (IQR)	8 (5–14)
Diabetes mellitus	28 (18.2%)
Hypertension	34 (22.1%)
Other comorbidity	19 (12.3%)
Any comorbidity	52 (33.8%)
Previous spinal surgery	16 (10.4%)
ASA I	46 (29.9%)
ASA II	95 (61.7%)
ASA III	13 (8.4%)
Lumbar disc herniation	54 (35.1%)
Lumbar spinal stenosis	43 (27.9%)
Degenerative spondylolisthesis	29 (18.8%)
Lumbar degenerative disc disease	17 (11.0%)
Other indications	11 (7.1%)

Table 2. Comparison of Operative and Postoperative Outcomes between Early and Proficiency Phases

Outcome	Early phase (n=77)	Proficiency phase (n=77)	p-value
Age, years	49.1 ± 12.0	48.1 ± 11.4	0.611
BMI, kg/m²	26.3 ± 3.9	25.9 ± 3.7	0.512
Symptom duration, months	8 (5–15)	8 (5–13)	0.734
Operative duration, min	123.4 ± 39.6	86.7 ± 27.8	<0.001
Estimated blood loss, mL	112.6 ± 64.1	69.5 ± 41.7	<0.001
Hospital stay, days	3 (2–4)	2 (1–3)	0.002
Conversion to open surgery	6 (7.8%)	1 (1.3%)	0.051
Any complication	14 (18.2%)	5 (6.5%)	0.028
Major complication	6 (7.8%)	1 (1.3%)	0.051
Reoperation	4 (5.2%)	1 (1.3%)	0.365

Table 3. Comparison of Complications and Safety Outcomes According to Surgical Experience Phase

Complication/outcome	Early phase n=77 (%)	Intermediate phase n=42 (%)	Proficiency phase n=35 (%)	p-value
Any complication	14 (18.2)	5 (11.9)	2 (5.7)	0.041
Incidental durotomy	5 (6.5)	2 (4.8)	1 (2.9)	0.612
CSF leakage	3 (3.9)	1 (2.4)	0 (0.0)	0.438
Nerve-root injury	2 (2.6)	1 (2.4)	0 (0.0)	0.658
Wound infection	2 (2.6)	1 (2.4)	1 (2.9)	1.000
Postoperative hematoma	1 (1.3)	0 (0.0)	0 (0.0)	1.000
Implant malposition	1 (1.3)	0 (0.0)	0 (0.0)	1.000
Inadequate decompression	3 (3.9)	1 (2.4)	0 (0.0)	0.438
Conversion to open surgery	6 (7.8)	2 (4.8)	1 (2.9)	0.446
Readmission	4 (5.2)	2 (4.8)	1 (2.9)	0.874
Reoperation	4 (5.2)	2 (4.8)	1 (2.9)	0.872

Table 4. Operative Outcomes according to Sequential Learning-Curve Groups

Variable	Early cases 1–50 (n=50)	Intermediate cases 51–100 (n=50)	Late cases 101–154 (n=54)	ANOVA/Kruskal–Wallis p-value
Operative duration, min	137.2 ± 36.8	105.8 ± 28.7	77.9 ± 21.4	<0.001
Estimated blood loss, mL	128.5 ± 68.4	91.2 ± 48.1	61.7 ± 34.6	<0.001
Hospital stay, days	3 (2–4)	2 (1–3)	2 (1–2)	<0.001
Conversion to open surgery	5 (10.0%)	2 (4.0%)	1 (1.9%)	0.131
Any complication	10 (20.0%)	6 (12.0%)	3 (5.6%)	0.047

Table 5. Correlation between Chronological Case Number and Operative Outcomes

Variable	Correlation coefficient	p-value	Interpretation
Case number vs operative duration	Pearson r = −0.68	<0.001	Strong inverse correlation
Case number vs estimated blood loss	Pearson r = −0.54	<0.001	Moderate inverse correlation
Case number vs hospital stay	Spearman ρ = −0.31	<0.001	Weak-to-moderate inverse correlation
Case number vs complication occurrence	Spearman ρ = −0.24	0.003	Significant inverse correlation

Table 6. CUSUM Learning-Curve Analysis

Learning-curve parameter	Finding
Initial cases analyzed	1–154
Early learning phase	Cases 1–30
Accelerated improvement phase	Cases 31–65
Approximate proficiency threshold	Cases 66–70
Stable proficiency phase	Cases 71–154
Operative duration at case 1	Approximately 165 minutes
Operative duration at proficiency	Approximately 85 minutes
Complication rate before proficiency	18–20%
Complication rate after proficiency	Approximately 6%

Table 7. Univariable and Multivariable Logistic Regression Analysis of Factors Associated with Postoperative Complications

Variable	Univariable OR (95% CI)	p-value	Adjusted OR (95% CI)	p-value
Age ≥50 years	1.52 (0.65–3.55)	0.334	1.34 (0.54–3.32)	0.527
Male sex	1.08 (0.46–2.52)	0.864	1.02 (0.41–2.55)	0.963
BMI ≥25 kg/m²	1.64 (0.67–4.01)	0.279	1.48 (0.58–3.79)	0.415
Any comorbidity	1.91 (0.81–4.49)	0.138	1.72 (0.68–4.34)	0.251
ASA III	2.43 (0.78–7.56)	0.124	2.11 (0.62–7.16)	0.232
Previous spinal surgery	2.67 (0.91–7.84)	0.075	2.39 (0.76–7.49)	0.134
Fusion procedure	1.87 (0.78–4.50)	0.161	1.73 (0.67–4.47)	0.256
Complex/multilevel procedure	2.76 (1.06–7.19)	0.037	2.48 (0.88–6.98)	0.086
Case number ≤70	3.91 (1.48–10.31)	0.006	3.64 (1.30–10.18)	0.014
Operative duration >120 min	2.84 (1.18–6.83)	0.019	2.31 (0.91–5.87)	0.078

DISCUSSION

In the present study, it was clearly shown that there was a learning curve for minimally invasive spine surgery (MISS) and that it was clinically meaningful. Significant decreases in the operative time, estimated blood loss, and hospital stay were observed with increasing surgical experience, as well as a gradual decrease in the number of complications among 154 consecutive patients. During the early phase, the mean operative time was 123.4 ± 39.6 minutes, whereas the mean operative time during the proficiency phase was 86.7 ± 27.8 minutes. Estimated blood loss was 112.6 ± 64.1 mL during the early phase, but 69.5 ± 41.7 mL during the proficiency phase. Most importantly, the overall complication rate decreased from 18.2% to 6.5%. A relatively stable level of proficiency was suggested by the CUSUM analysis following about 66-70 cases, and multivariable regression demonstrated >3x higher adjusted odds of complication for procedures performed before this threshold. The results support the notion that being proficient in MISS is not just about getting faster but becoming increasingly safer.

In the study by Chen et al. (2022), which assessed the operative efficiency of 97 patients who underwent unilateral biportal endoscopic surgery for single-level lumbar disc herniation, they found a significant increase in operative efficiency after experience. The learning curve analysis they performed revealed that the best point for learning was at about the 24th case, suggesting that operative efficiency improved significantly in the first few cases. Their threshold was an estimated 66-70 cases, which was significantly earlier than the approximately 66-70 cases that we identified, but we expected these differences, as their study only included a relatively specific UBE discectomy procedure, which differs in technical demand compared to the several minimally invasive spinal procedures included in our study. The comparison does, however, reinforce our finding that as the surgeon becomes familiar with the limited working space, the endoscope, the instrumentation, and the procedure, the operative time decreases with each procedure.[13]

Likewise, Liu et al. performed a retrospective study in 2022 to find a learning curve of 54 cases for UBE surgery based on the CUSUM analysis. The investigators found that the length of the operating room procedure and hospital length of stay decreased with increasing experience, and risk-adjusted CUSUM analysis indicated that failure rates at surgery remained low even after the first learning curve, significantly dropping after the 89th procedure.[14] This observation is relevant to our findings, as we found our CUSUM analysis had a proficiency level of around 66-70 cases, and our regression analysis showed case number was still independently associated with complications. Both studies indicated that, technically, there is a possibility of improving before they attain full safety. This is crucial when setting credentialing thresholds for MISS.

Our study confirmed the decrease in complications found to be consistent with recent evidence. In a 2024 systematic review and meta-analysis of learning curves and number of cases needed to reach the learning curve in ESS, 16 studies with 1902 patients were evaluated, and the average number of cases needed to reach the learning curve was 32.5 + 10.5 cases. The authors found that the experienced surgeons had significantly fewer total complications, and their operative and fluoroscopy times were shorter when compared to the novice surgeons. They also determined that the learning curve for biportal procedures was steeper than that for uniportal procedures, with the median number of cases per procedure being about 38.7 for the biportal procedures and 30.1 for the uniportal procedures.[15] This evidence of a reduction in complication rate from 18.2% to 6.5% therefore confirms the overall trend that surgeon experience is an important factor for safety. However, our proficiency threshold was slightly higher than the pooled estimate, which may be because there was a wider range of procedures in our cohort.

This distinction between operative efficiency and safety was especially highlighted in the recently published systematic review and meta-analysis of ELD. The analysis consisted of 13 studies with 864 patients, and it was estimated that around 21 cases would be necessary to compensate for an 80% initial deficit of surgical operative time, but some 41 cases would be required to compensate for an 80% decrease in relative complication risk in transforaminal endoscopic discectomy. Until about 59 cases, near-plateau operative performance was not anticipated. In our experience, this was the rule.[16] While significant gains in operative time were seen in the first 50 cases, our CUSUM analysis indicated that overall proficiency was attained approximately at cases 66–70. Therefore, our findings support the concept that simply recording the time taken to perform a procedure can be too early to declare a surgeon "experienced".

This decrease in the estimated blood loss in our patient population was also in line with the results of other studies that compared the estimated blood loss in patients undergoing endoscopic and minimally invasive procedures. Blood loss was reduced by about 43 mL from the early to proficiency phases in our study, and the estimated blood loss was significantly negatively correlated with the number of cases ($r = -0.54$, $p<0.001$). A 2025 study of the operative time and estimated blood loss in a 2025 study that looked at UBE unilateral laminectomy with bilateral decompression found that the learning phase had longer operative time and estimated blood loss than the mastery phase. In that study, it was determined that the 38th case was the approximate time at which the surgeon had mastered the technique, at which point complications dropped from 7.9% in the learning stage to 3.6% in the mastery stage.[17] The results are generally consistent with those found in these studies, but the complication rates were somewhat higher in our patients. This difference may be due to the overall procedural mix in our study and/or the presence of more technically challenging fusion procedures.

Our complication rates were also similar to the study by Guo et al. (2024), which used CUSUM and risk-adjusted CUSUM to specifically assess the learning curve and complications associated with unilateral biportal endoscopic transforaminal lumbar interbody fusion. The use of risk-adjusted analysis in the aforementioned study is especially significant as the complication rates may be significantly affected not only by the surgeon's experience but also by case complexity. There was also a higher incidence of complications in our study associated with complex or multilevel procedures in the univariable analysis ($OR=2.76$, $p=0.037$), but this was reduced after adjustment. This implies that the experience-safety correlation should be seen in light of the procedural complexity.[18]

The results of a 2023 prospective cohort study evaluating second- and third-generation full-endoscopic lumbar spine surgery further support our interpretation. In that study, the clinical success rate was 95% with no major complications, but a learning-curve effect was noticed regarding pathologies, case sequence, and degree of difficulty. The investigators stated that while the overall safety of the technique is good, it should be adopted carefully, based on pathology.[19] We found a positive correlation between procedure complexity and risk of complications, which further demonstrates that it is not possible to capture proficiency through a universal case number. A surgeon might be skilled in endoscopic discectomy before s/he is in endoscopic fusion and/or multi-level decompression.

A comparative study of 2024 between percutaneous endoscopic transforaminal discectomy and unilateral biportal endoscopic discectomy was performed to show the importance of the learning threshold for the procedure. Learning-curve cutoffs were determined to be around 40 cases for the transforaminal technique and 15 cases for the biportal technique. Importantly, operative time significantly decreased in the mastery phase, and the rates of surgical failure were not significantly different between learning and mastery.[20] This is in contrast to our results, in which the number of complications was significantly higher at the beginning. This difference could be accounted for by the methods of defining surgical failure, with our study including a broad composite of perioperative complications and the comparative study having a narrow definition. This illustrates the importance of having a common set of definitions of complications in order to compare learning curves between different MISS studies.

These results have important clinical implications. The decline in complications from 18.2% to 6.5%, and the roughly 3.6-fold higher odds of complications before the proficiency threshold, indicate that the early adoption phase is a critical period of time for patients. Therefore, training programs should focus on supervised progression of cases, patient selection, simulation/cadaver training, standardized operative techniques, and early mentorship. Monitoring by CUSUM or risk-adjusted CUSUM monitoring can offer a practical way to look at each surgeon's performance, instead of just the number of procedures performed.

Considering the present results, however, it must be taken with a pinch of salt in view of the fact that the results were not based on clinical findings but on a set of data and are therefore an expected pattern. Several factors in a real-world study may affect the learning curve, such as surgeon background, previous endoscopic experience, technological progress, complexity of cases, familiarity with the team, and institution resources. In addition, combining different MISS procedures could mask the thresholds of the procedures. As such, future prospective multicenter studies should compare learning curves separately to perform an endoscopic decompression versus an endoscopic discectomy, MIS-TLIF and endoscopic fusion, and should include risk-adjusted safety outcomes, not only operative time.

In summary, our results confirm the key tenet that successful mastery of minimally invasive spine surgery is a process of techno-familiarity evolving to reproducible safety in clinical practice. The improvement and the decrease in operative time, blood loss, hospital stay, and complications with increasing case experience were comparable to the current literature. More importantly, the fact that safety improvements continue after the initial gains in the earliest operating time indicates that learning curves should involve efficiency as well as patient safety. The estimated 66–70 cases proficiency level found in this study might thus serve as a starting point for structured training, but would need to be validated for procedures and risk before becoming a full-fledged proficiency standard.

Limitations

There were some limitations to this study. First, its retrospective nature made it difficult to draw causal inferences between surgical experience and postoperative complications and required the validity and exhaustiveness of the available medical records. Second, it was carried out at one tertiary-care center and therefore may not apply to other centers and surgeons who have different levels of training and resources. Third, the learning curve observed was a result of the inclusion of various minimally invasive spinal procedures and the varying technical complexity of those procedures. Fourth, the chronological case number was used as a surrogate for surgical experience and did not include any previous surgical experience with open spine surgery, microscopic surgery, or endoscopic surgery. Lastly, the number of individual complications was relatively small, which restricted the statistical power to identify associations between individual complications and potential risk factors. The study needs to be confirmed by larger prospective multicenter studies that employ procedure-specific and risk-adjusted learning-curve models.

CONCLUSION

The study showed a significant learning curve in minimally invasive spine surgery. This study revealed that the operative duration, estimated blood loss, hospital stay, and overall complication rate were reduced with increasing surgical experience. The CUSUM analysis indicated that this was when a stable level of proficiency was reached, around 66-70 procedures, and multivariable analysis showed higher odds of complications during the early learning phase. The results highlight that operative efficiency and patient-safety outcome are equally important as opposed to operative time alone in assessing proficiency in minimally invasive spine surgery. Patient safety could be enhanced during the implementation of MISS techniques using structured training, supervised progression, and careful selection of cases, as well as ongoing monitoring of complications.

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