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Clinical Study

The learning curve for performing three-column osteotomies in adult spinal deformity patients: one surgeon's experience with 197 cases

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Abstract

BACKGROUND CONTEXT: Three-column osteotomy (3CO) is used to correct rigid adult spinal deformity. It presents risk of complications because it involves extensive osseous resection and spinal destabilization.

PURPOSE: Our purpose was to characterize the learning curve for performing 3CO in adult spinal deformity patients.

DESIGN: Retrospective review.

PATIENT SAMPLE: A surgical registry at a tertiary care center was used to identify 238 cases of 3CO for correction of adult spinal deformity by 1 surgeon between 2005 and 2014. Patients with at least 1 year of clinical and radiographic follow-up were included (n=197; mean duration of follow-up, 43 months; range, 12−121).

OUTCOME MEASURES: We quantified associations between surgeon experience and (1) estimated blood loss per vertebral level fused (EBL/VLF), (2) incidence of new neurologic deficits, (3) incidence of reoperation for instrumentation failure, (4) operative time in minutes, and (5) magnitude of correction at the level of the osteotomy.

METHODS: The learning curve for binary outcomes was demonstrated using a LOWESS smoother plot of the probability of occurrence. Change in risk was calculated using a generalized linear model with link identity and binomial family. The learning curve for continuous variables was demonstrated using a scatter plot and a line of best fit based on linear regression analysis. Alpha=0.05.

RESULTS: EBL/VLF decreased by a mean of 19.7 mL (95% confidence interval [CI]: 11.3−28.1) with each 10 cases (decrease of 388 mL/level fused by the end of the study period). The risk of a neurologic deficit declined by 7.98% (95% CI: 7.98%, 7.99%) with every 100 cases. The risk of reoperation declined by 1.99% (95% CI: 0.83%, 3.17%) with every 10 cases until the 100th case. After that point, there was no significant change in the probability of reoperation (p>.05). The magnitude of correction and operative time did not change with increasing surgeon experience (p>.05).

CONCLUSION: Incidence of reoperation for instrumentation failure, incidence of new neurologic deficits, and estimated blood loss improved with increasing surgeon experience at performing 3CO. Most outcomes, except the risk of reoperation, improved through the last case.

FDA device/drug status: Not applicable.

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Approval was obtained from our institutional review board.

Level of Evidence: III

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Introduction

Three-column osteotomy (3CO) is a powerful tool for achieving anatomic alignment and improving health-related quality of life in patients with severe, rigid spinal deformities [1−4]. Despite the effectiveness of 3CO, however, the decision to use it must be weighed against the potential for complications. Several studies have reported a substantial risk of perioperative neurologic deficits [5−8] and instrumentation failure [9−12]. Furthermore, the extensive osseous resection and destabilization involved in 3CO are often accompanied by considerable blood loss and long operative times [5,7−9].

Because of the high risk for complications as well as the unique anatomic parameters that place the spinal cord and its accompanying neural structures in an intimate relationship with the bony anatomy [13], performing a vertebral osteotomy involves different technical considerations compared with osteotomies elsewhere in the human skeleton. Therefore, characterizing the surgeon's learning curve for 3CO is of paramount importance, particularly in the context of medical education and training, as well as to safeguarding patients' well-being. To our knowledge, only one study has characterized the learning curve for performing pedicle subtraction osteotomies, specifically [14]. The study offers insight into the association between surgeon experience and short-term outcomes, but it does not address other outcomes that require longer follow-up, such as instrumentation failure, or outcomes that may substantially affect patients' lives, such as neurologic deficits.

The aims of this study were to characterize the learning curve for performing 3CO in adult spinal deformity patients by quantifying the association between surgeon experience and the incidence of reoperation for instrumentation failure, incidence of new neurologic deficits, estimated blood loss per vertebral level fused (EBL/VLF), operative time, and the magnitude of focal correction at the level of the osteotomy.

Methods

Patient sample

Data were obtained from a spine surgery registry at a tertiary care academic center. This is a retrospective case series of consecutive cases of 3CO performed by one fellowship-trained orthopedic spine surgeon between 2005 and 2014, beginning during the early career period. Before this series, the surgeon had experience with hemivertebra resection in congenital scoliosis patients and had performed approximately 15 3COs after fellowship training. Approval was obtained from our institutional review board. We included adults who underwent a posterior-only 3CO (vertebral column resection or pedicle subtraction osteotomy) [15] and who completed at least 1 year of clinical and radiographic follow-up. Cases were assigned consecutive identification numbers on the basis of the date of surgery.

Radiographic parameters

The radiographic parameters assessed were sagittal vertical axis (measured as the distance between the plumb line from the center of C7 to posterior S1), lumbar lordosis (upper endplate of L1 to lower endplate of S1), thoracic kyphosis (upper endplate of T4 to lower endplate of T12), thoracic major curve (upper endplate of T3 to lower endplate of T12), and lumbar major curve (upper endplate of T12 to lower endplate of L4). We also measured the focal angles (sagittal and coronal) at the level of the osteotomy, which were defined as the angles between the superior endplate of the vertebra above the level of resection and the lower endplate of the vertebra below. All measurements were performed using full-length standing scoliosis radiographs.

Technical note and change in surgeon's perspective

Throughout this series, the senior author has learned that patient selection and the location of the 3CO site are critical to successful outcomes after 3CO, with the ideal patient having previous rigid fusion of multiple levels. This allows for a 3CO to be performed without a mobile segment immediately caudal to the osteotomy site. Over time, the senior author's technique for performing pedicle subtraction osteotomies has evolved to include the cephalad disc (Schwab type IV) [15]. The development of a lamina-sparing decompression technique has provided the ability to preserve a much larger fusion surface, as opposed to conventional laminectomy [16].

Outcomes

The learning curve for 3CO was assessed using the following outcomes: (1) change in estimated blood loss per level fused (assessed using estimated blood loss/number of vertebral levels fused); (2) incidence of a new nerve root deficit postoperatively; (3) incidence of instrumentation failure (defined as reoperation for unilateral or bilateral rod fractures at any vertebral level); (4) operative time from incision to skin closure; and (5) the magnitude of focal correction at the level of the osteotomy. To determine the incidence of new nerve root deficits, we used the American Spinal Injury Association [17] Lower Extremity Motor Score (LEMS) to evaluate lower extremity motor function. This score grades motor function on a scale of 0 (no motor function) to 5 (full motor function) for five lower extremity muscle groups: hip flexors (psoas-L2), knee extension (quadriceps-L3), ankle and toe dorsiflexion (anterior tibialis-L4), great toe extension (extensor hallucis longus-L5), and plantar flexion (gastric soleus-S1). The LEMS has a maximum of 50 points (25 points per side). The LEMS was calculated for each patient at baseline and immediately after surgery (up to 2 weeks). Patients were assigned to two groups: the “intact” group included patients with preoperative LEMS of 50, and the “deficit” group consisted of patients with perioperative LEMS <50. Our outcome of interest was the incidence of a neurologic deficit (LEMS<50) in a previously neurologically intact patient.

Statistical analysis and the learning curve

Baseline patient characteristics, surgical parameters, and radiographic deformity measurements were compared between the first 100 cases and the patients thereafter using Student *t* tests or chi-squared tests, as appropriate. EBL/VLF, operative time, and the amount of the focal correction were treated as continuous variables. The incidence rates of a new postoperative spinal cord or nerve root deficit and instrumentation failure were treated as binary variables. The learning curve for binary variables was demonstrated using a LOWESS smoother plot for the probability of outcome occurrence. A generalized linear model with a link identity and binomial family was then used to calculate the risk difference with increasing caseload. For neurologic deficits, there appeared to be an inflection point at approximately the 100th case, and thus a piecewise generalized linear model was used.

The learning curve for continuous variables was demonstrated using a scatter plot of the outcome as a function of caseload along with the line of best fit from linear regression analysis. Robust estimates of the standard error were used in all regression analyses. Statistical analyses were performed using Stata, version 15, software (StataCorp LP, College Station, TX). Significance was set at p<.05.

Results

Patient sample

We identified 238 cases of 3CO, of which, 197 (83%) had complete 1-year follow-up and were included in the analysis. Mean follow-up was 43 months (range, 12−121). The mean patient age was 58 years (range, 19−81) and 142 patients (72%) were women. The mean Charlson Comorbidity Index value was 2 (range, 0−7). The number of annual cases included in the analysis ranged from 13 to 26. The mean SVA was 13.2 cm (range, −6.4 to 35). Fifty-four percent (n=107) of patients underwent pedicle subtraction osteotomy, and 65% (n=128) of patients underwent revision as opposed to primary surgery. Most osteotomies (72%, n=142) were in the lumbar spine. The mean focal correction in the sagittal plane was 32° (range, −5° to 89°), and the mean focal correction in the coronal plane was 10° (range, −13° to 33°).

Changes in baseline patient characteristics

The proportion of patients older than 65 years became significantly higher after the 100th case (39%) compared with the first 100 cases (26%) (p=.048), as did the proportion of patients with a Charlson Comorbidity Index value of >1 (57% vs 38%, respectively; p=.009). The proportion of women did not change significantly over time (p=.509). After the 100th case, a higher proportion of cases were revisions (72% vs 58%, respectively; p=.037) and a higher proportion of patients had a preexisting neurologic deficit (32% vs 16%, respectively; p=.009).

Changes in surgical and radiographic parameters

The mean number of vertebral levels fused was significantly greater after the 100th case (10.4 levels) vs the first 100 cases (8.8 levels) (p=.006). The proportion of patients who underwent vertebral column resection (54% vs 38%, p=.028), as well as the use of interbody cages (95% vs 64%, p<.01) increased significantly after the 100th case vs the first 100 cases, respectively. There was a trend toward more thoracic osteotomies after the 100th case (34% vs 22%, p=.060). Of all baseline radiographic parameters assessed, only thoracic major curve was significantly different between the first 100 cases and the subsequent cases (Table 1).

Outcomes

EBL/VLF

EBL was available for 164 cases. The mean EBL/VLF was 306±333 mL. There was a linear decline in EBL/VLF as the caseload increased (Fig. 1). Simple linear regression was used to estimate the mean decline in EBL/VLF, which was 19.7 mL/10 cases (95% confidence interval [CI]: 11.3−28.1). This incremental decline would be equivalent to approximately 100 mL of blood loss in a 5-level fusion surgery with every 10 cases performed.

Neurologic deficit

Thirteen patients had no neurologic deficit (LEMS=50) at presentation and experienced a new postoperative deficit after surgery (LEMS<50; Table 2). There was a decline in the incidence of neurologic deficit as the caseload increased (Fig. 2). The risk of a neurologic deficit declined by 7.98% (95% CI: 7.98, 7.99) with every 100 cases.

Instrumentation failure

Fifteen patients (7.6%) underwent reoperation for instrumentation failure (11 bilateral and 4 unilateral). Four (2%) of the cases requiring reoperation for instrumentation failure involved rod fracture at the level of the osteotomy (Table 2). LOWESS for the probability of reoperation for instrumentation failure at any vertebral level showed a steady decline with each subsequent case until the 100th case, after which there was a plateau (Fig. 3).

Table 1
Characteristics of 197 patients who underwent 3CO by 1 surgeon for the correction of spinal deformity between 2005 and 2014

	First 100 cases		Cases 101−197		
Parameters	N (%)	Mean±SD	N (%)	Mean±SD	p Value
Demographic characteristics					
Age >65 y	26 (26)		38 (39)		.048
Charlson Comorbidity Index >1	38 (38)		55 (57)		.009
Female sex	70 (70)		72 (74)		.509
Revision surgery	58 (58)		70 (72)		.037
Preoperative neurologic deficit	16 (16)		31 (32)		.009
Surgical parameters					
Interbody cage	64 (64)		95 (95)		<.01
Thoracic osteotomy	22 (22)		33 (34)		.06
Vertebral column resection	38 (38)		52 (54)		.028
No. of vertebral levels fused		8.8±3.9		10±4.3	.006
Spinal deformity, °					
Sagittal vertical axis		13±9.9		13±9.1	.824
Thoracic kyphosis		46±28		48±23	.517
Lumbar lordosis		31±25		33±33	.607
Thoracic major curve		42±24		31±12	.029
Lumbar major curve		38±18		40±19	.683

SD, standard deviation.

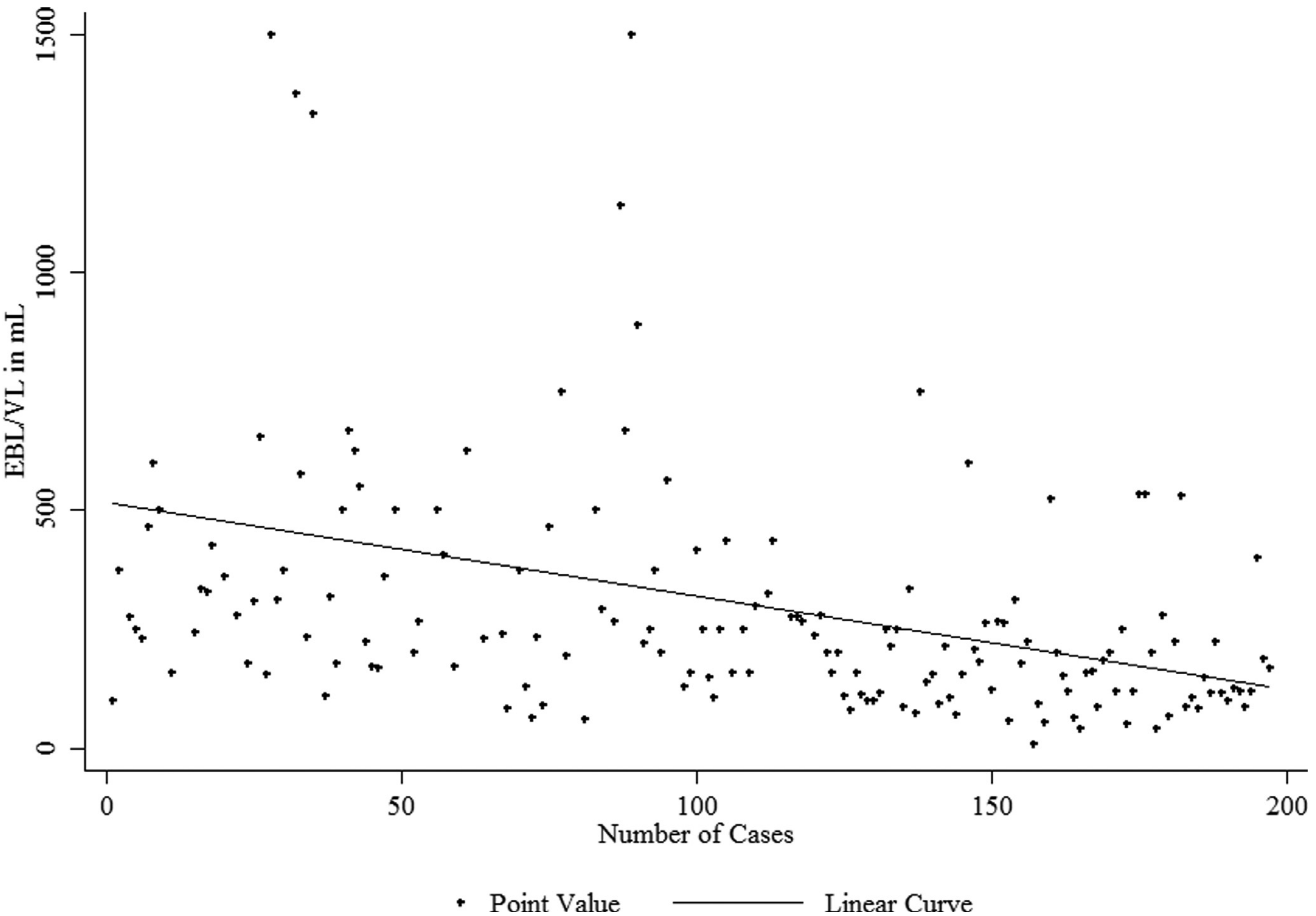

Fig. 1. Change in estimated blood loss per vertebral level fused as a function of case load. Calculated on the basis of 164 patients who underwent 3CO by 1 surgeon for the correction of spinal deformity between 2005 and 2014.

Table 2
Neurologic deficit and reoperations among 197 patients who underwent 3CO by 1 surgeon for the correction of spinal deformity between 2005 and 2014

		New postoperative neurologic deficits		No. of patients who underwent reoperation	
Year	No. of patients	No. of patients	LEMS*	Instrumentation failure	Bilateral rod fracture
2005	13	2	22, 44	1 (8)	0 (0)
2006	21	2	46, 48	4 (19)	3 (14)
2007	15	2	42, 46	2 (13)	1 (7)
2008	16	3	18, 41, 42	2 (13)	1 (6)
2009	21	0	NA	1 (5)	1 (5)
2010	21	2	30, 39	0 (0)	0 (0)
2011	26	1	41	0 (0)	0 (0)
2012	20	0	NA	2 (10)	2 (10)
2013	26	1	43	2 (8)	2 (8)
2014	18	0	NA	1 (6)	1 (6)

LEMS, lower extremity motor score; NA, not applicable.
* Postoperative LEMS in patients who were neurologically intact preoperatively and who developed a new neurologic deficit.

The risk of reoperation declined by 1.99% (95% CI: 0.83, 3.17) with every 10 cases until the 100th case. After that point, there was no significant change in the probability of reoperation (risk difference=0.094; p=.20; 95% CI: 0.05, 0.24).

Operative time

The median operative time in this study was 7.2 hours (interquartile range=5.5, 9.2). There was no significant change in operative time with increasing surgeon experience (=1.60; 95% CI: −1.92, 5.12; Fig. 4).

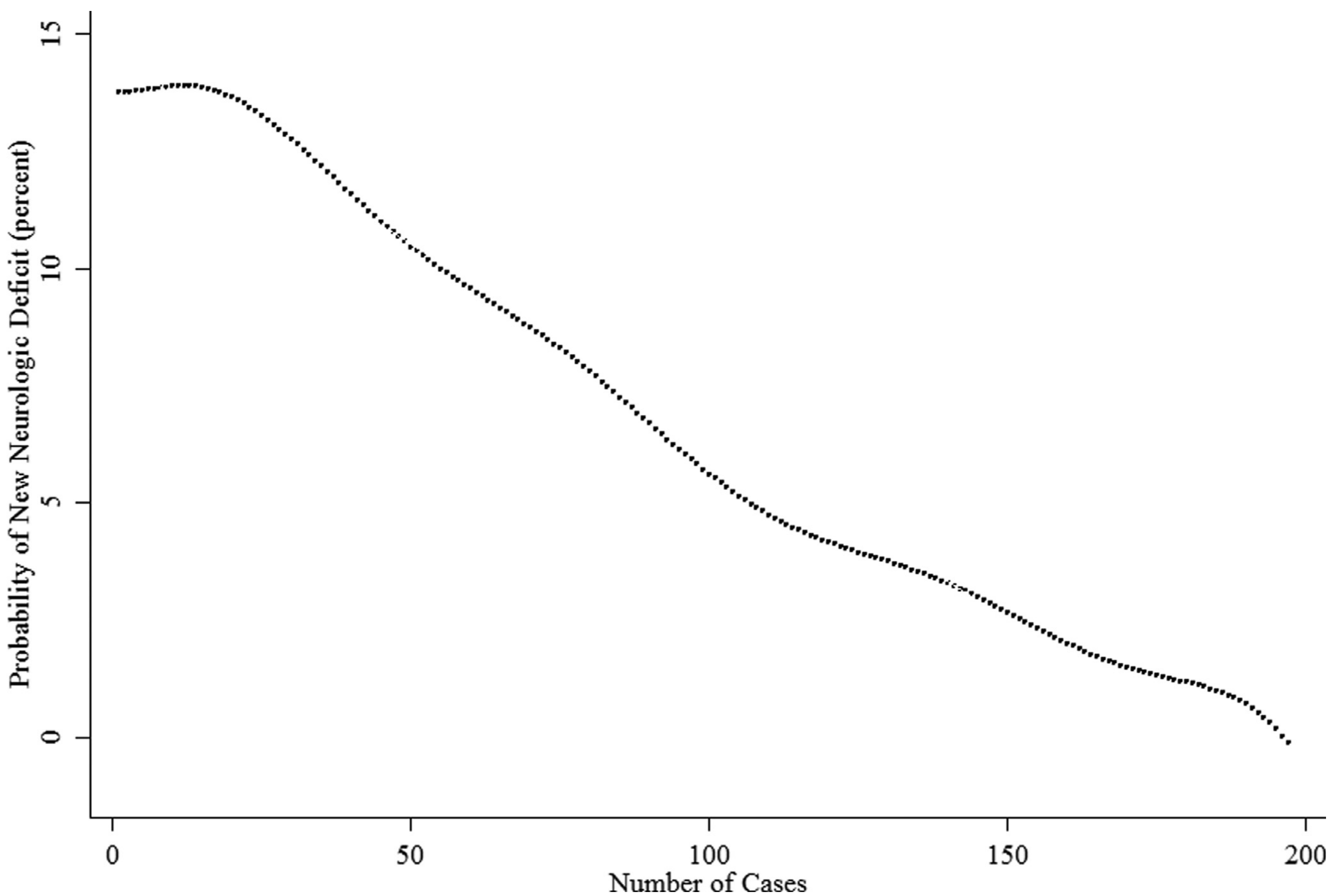

Fig. 2. The risk of developing a new neurologic deficit as a function of case load. Plotted on the basis of 197 patients who underwent 3CO by 1 surgeon for the correction of spinal deformity between 2005 and 2014.

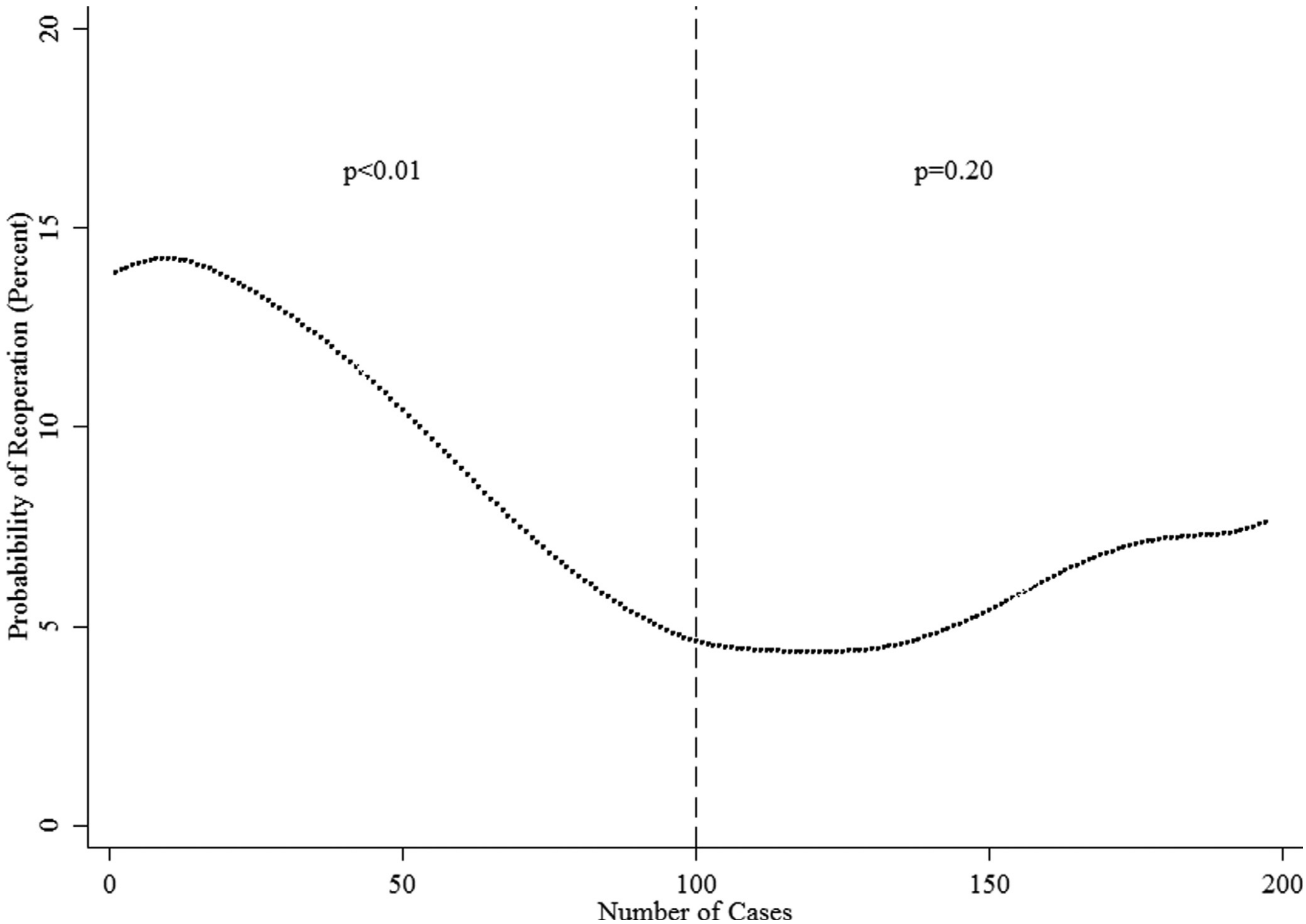

Fig. 3. The risk of reoperation for instrumentation failure as a function of case load. Plotted on the basis of 197 patients who underwent 3CO by 1 surgeon for the correction of spinal deformity between 2005 and 2014.

Focal correction

The mean sagittal and coronal correction at the osteotomy sites was 32° and 10°, respectively. Interestingly, the amount of focal correction (coronal or sagittal) did not change significantly with increasing surgeon experience (p>.05).

Discussion

We used a caseload-outcome analysis to examine and quantify the learning curve for performing 3CO on the basis of 1 surgeon's experience with 197 patients who completed at least 1 year of clinical and radiographic follow-up. Increasing surgeon experience was associated with a significant improvement in most postoperative outcomes.

Learning curves for various spine surgical procedures have been described in the setting of pediatric spinal deformity [18,19] and less invasive adult procedures, including anterior cervical discectomy and fusion [20], minimally invasive lumbar spine decompression [21], and transforaminal lumbar interbody fusion [22]. Despite having used different statistical methods than those used in our study to assess the learning curve, these studies reported that a fewer number of cases (<60) were associated with significantly improved outcomes. In the case of anterior cervical discectomy and fusion [20], for example, the authors reported that 90% of potential improvement in blood loss and fusion rates occurred by cases 56 and 57. In our series, the improvement in instrumentation failure plateaued only after the 100th case, and blood loss continued to improve throughout the series. This contrast highlights the importance of surgeon experience in improving outcomes and lowering complications in complex spinal deformity surgery involving 3CO.

Bourghli et al. [14] reported on 102 consecutive pedicle subtraction osteotomies performed by 1 surgeon. The analysis was based on arbitrary cutoffs involving case date. The authors showed that blood loss decreased significantly with increasing surgeon experience. This is similar to the findings in our study, although we were able to quantify the improvement and visualize the learning curve based on cumulative caseload. Additionally, our study has longer follow-up than the aforementioned study, in which radiographs taken at 3 months only were used to determine immediate postoperative stability. This is an important

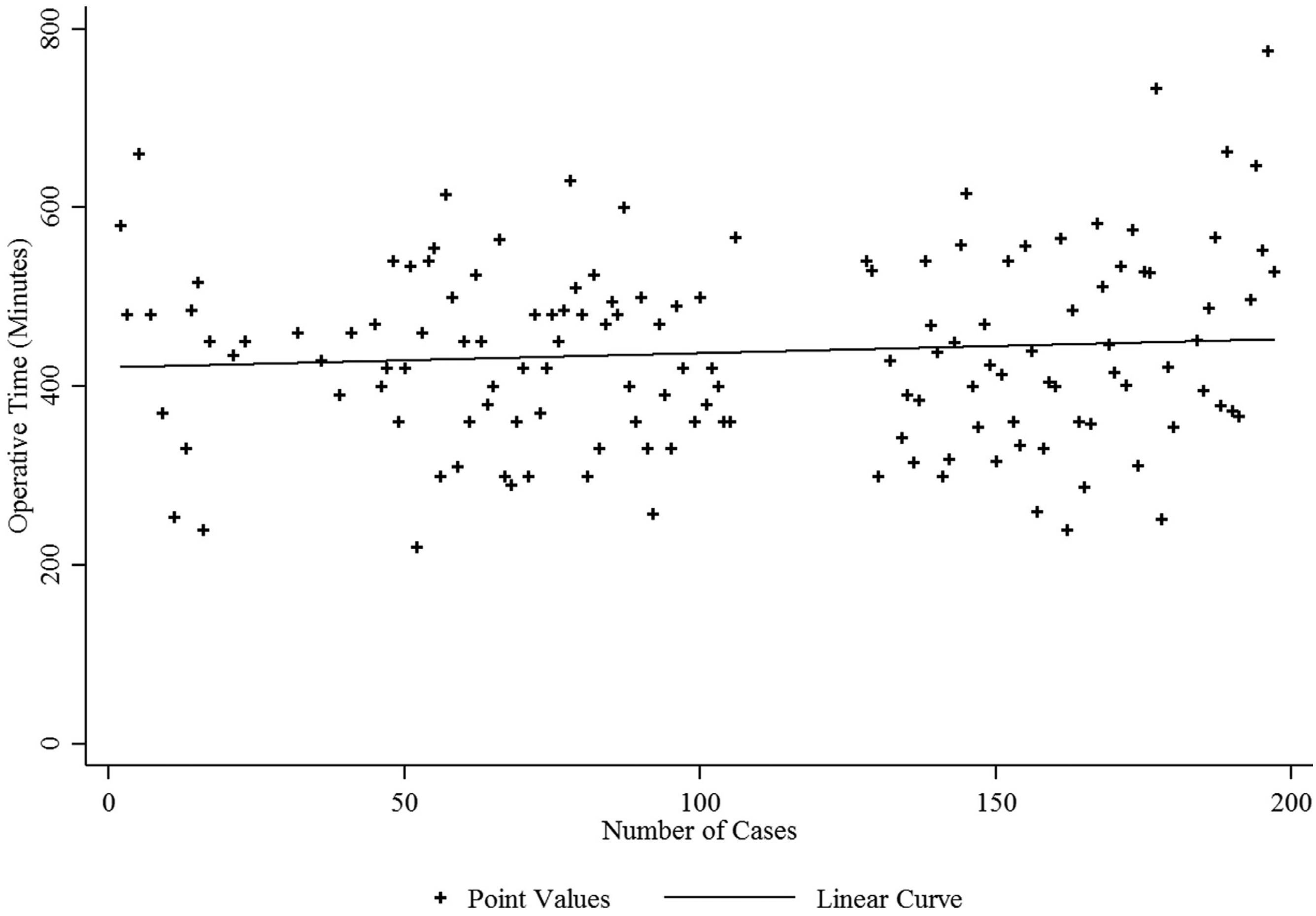

Fig. 4. Change in operative time in minutes as a function of case load. Calculated on the basis of 142 patients who underwent 3CO by 1 surgeon for the correction of spinal deformity between 2005 and 2014.

consideration because longer follow-up allowed us to assess construct stability, which affects the likelihood of successful fusion and maintenance of correction.

The shifting demographic characteristics and surgical parameters in our study showed a propensity by the senior surgeon to perform 3COs on more challenging, higher risk patients who were older, who were undergoing revision procedures, and who were presenting with preexisting neurologic deficits as time went on. In fact, after the 100th case, 72% of patients were undergoing revision surgery. Furthermore, there was a higher proportion of vertebral column resections and osteotomies in the thoracic spine, which are generally considered higher risk than other procedures in the lumbar spine. This shift reflects the surgeon's increasing confidence in his ability to perform such procedures and an inclination to use this technique to correct deformities across a preexisting fusion mass.

During the study period, interbody fusion devices for anterior structural support were also used increasingly to aid in deformity correction and to improve fusion rate. In addition, a notable change during the study period was the introduction of the "en bloc reduction fixation technique" as opposed to more traditional constructs, whereby the segments caudal and cephalad to resection are instrumented, connected separately, and then manipulated onto an intercalary rod to achieve the desired focal and global alignment and reduce strain on the instrumentation across from and adjacent to the osteotomy site. We attribute the observed decrease in the rate of instrumentation failure to both the addition of anterior structural support and interbody devices, and techniques such as en bloc reduction fixation. In addition, advancement in pelvic fixation during the course of this series allowed for more confidence in performing distal lumbar osteotomies that permitted a greater degree of deformity correction when indicated. Although the prospect of high complication rates that would take years to decrease is daunting, this should not discourage young spine surgeons from performing complex procedures like 3COs entirely. However, unlike other spinal procedures, the performance of a 3CO may warrant the supervision of a more experienced surgeon early in one's practice.

One limitation of our study is that these results are based on one surgeon's experience, as are most learning curve studies, and thus may not represent every surgeon's experience. Additionally, our study is subject to the risk of selection bias inherent in a retrospective design. Another potential limitation is the minimum follow-up period of 1 year. Despite the facts that neurologic deficits are evident during the immediate postoperative period and that a substantial proportion of instrumentation failure−related reoperations occur within the first year after surgery [9], longer follow-up time may reveal higher reoperation rates. Because of this limitation, we did not discuss the association between time to reoperation and surgeon experience in the present study. However, we believe this is the largest case series of 3COs performed by one surgeon to evaluate learning curve. Additionally, it is the first study to assess the relationship between the learning curve and important outcomes, such as neurologic deficits and instrumentation failure, with longer term follow-up. Thus, we believe that these results are applicable to spinal deformity surgeons at various career stages.

Conclusion

The learning curve for 3CO shows substantial improvements in the incidence of reoperation for instrumentation failure, incidence of new neurologic deficits, and estimated blood loss with increasing surgeon experience. Most outcomes, except for the risk of reoperation, which plateaued after the 100th case, improved up until the last case.

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