European Spine Journal (2018) 27:652–660
https://doi.org/10.1007/s00586-018-5481-8

ORIGINAL ARTICLE

102 lumbar pedicle subtraction osteotomies: one surgeon's learning curve

Anouar Bourghli[1] · Derek Cawley[2] · Felipe Novoa[2] · Manuela Rey[2] · Abdulmajeed Alzakri[2] · Daniel Larrieu[2] · Jean-Marc Vital[2] · Olivier Gille[2] · Louis Boissiere[2] · Ibrahim Obeid[2]

Received: 21 August 2017 / Accepted: 16 January 2018 / Published online: 30 January 2018

Abstract

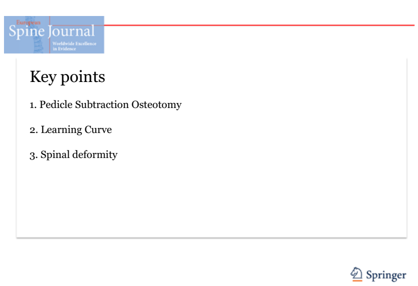
Purpose Pedicle Subtraction Osteotomy (PSO) is an effective surgical technique for the correction of fixed sagittal malalignment of the spine. It is a demanding technique that requires a long learning curve. The aim of this study is to analyze a surgeon's learning curve for lumbar PSO in relation to the preoperative, perioperative, and postoperative management, with assessment of the global outcome.

Materials and methods 102 patients operated over an 8-year period were included, distributed in 3 groups over the time, and retrospectively analyzed. The following data were collected: demographic characteristics, preoperative and postoperative radiological parameters, operative technical details, and complications. Multiple regression analysis was performed, and while the number of cases was the predictor, other variables such as demographic, radiographical, and surgical variables were considered as a covariate in the final model.

Results When comparing the first group and the last group of patients, the mean surgical time had decreased by 50 min, the estimated blood loss was decreased by 655 ml, and a significant decrease in dural tear occurrence was noticed. In addition, we found a significant decrease in the hospital stay length. Multivariate linear regression analysis showed that when the surgeon's experience doubles, the operative time decreases by 29 min, the blood loss by 281 ml, and the odds of hospital stay ≥ 21 days decrease by 0.66 times.

Conclusion PSO technique has a relatively long learning curve. This study showed that accumulating the experience over the years, while performing cases on a regular basis, is definitely the key in mastering this complex and risky technique, with significant improvements in the perioperative parameters that directly impact the recovery and global outcome.

Graphical abstract These slides can be retrieved under Electronic Supplementary Material.



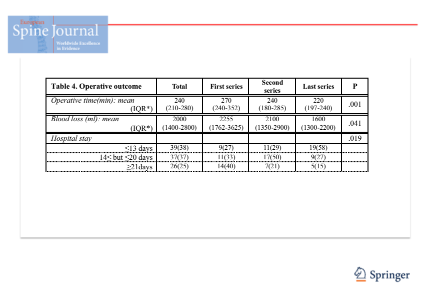
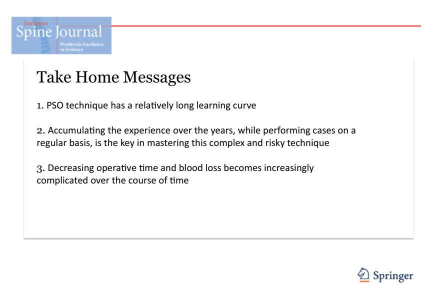


Table 4. Operative outcome	Total	First series	Second series	Last series	P
Operative time(min): mean (IQR*)	240 (210-280)	270 (240-352)	240 (180-285)	220 (197-240)	.001
Blood loss (ml): mean (IQR*)	2000 (1400-2800)	2255 (1762-3625)	2100 (1350-2900)	1600 (1300-2200)	.041
Hospital stay					.019
≤13 days	39(38)	9(27)	11(29)	19(58)	
14≤ but ≤20 days	37(37)	11(33)	17(50)	9(27)	
≥21days	26(25)	14(40)	7(21)	5(15)	



Keywords Pedicle subtraction osteotomy · Learning curve · Single surgeon · Spinal deformity · Sagittal balance · Global alignment

Electronic supplementary material The online version of this article (https://doi.org/10.1007/s00586-018-5481-8) contains supplementary material, which is available to authorized users.

Extended author information available on the last page of the article

Introduction

In the last 20 years, sagittal malalignment has become a central theme in the outcomes of adult spinal deformity, particularly with its relation to lumbopelvic parameters and its impact on the patients' quality of life [1–3]. 65% of lumbar lordosis (LL) is measured between L4 and S1 in a normal cohort [4], and a loss of LL can progressively occur with degenerative changes affecting the low lumbar spine. In addition, this flatback deformity can occur with spinal surgery, fracture, or ankylosing spondylitis. The sagittal malalignment caused by the loss of lordosis prompts compensatory mechanisms such as pelvic tilt with hip extension, thoracic and cervical extension, and knee flexion, cumulatively resulting in deterioration of quality of life [5].

Restoration of LL is correlated with improvement in quality of life and in the case of rigid deformity can be achieved through Pedicle Subtraction Osteotomy (PSO) [6]. This demanding technique is best indicated for the correction of fixed sagittal and combined malalignment of the spine and has a high rate of complications [7–9].

As for any surgery, technical improvements are subject to progressive refinement over time, which is accomplished through intraoperative training as resident or fellow, cadaveric simulation, evaluation of current literature, instrumentation evolution, and primary operator experience. There is no study in the literature describing the learning curve of a spinal deformity surgeon over the time with PSO technique.

The objective of this study is to report the experience of a single surgeon in more than 100 lumbar PSOs and to describe the learning curve of this specific technique, over and 8-year period.

Materials and methods

Retrospective analysis of a consecutive case series of lumbar PSOs in a single institution and a single surgeon experience between November 2005 (date of the first lumbar PSO) and July 2013.

Analyzed variables

PSO cases were collected from a database of more than 2.000 spine procedures done by one surgeon over an 8-year period between November 2005 and July 2013. Patients who underwent only a lumbar PSO were selected. The following data were collected: demographic characteristics, various preoperative (PreOp) radiological parameters, operative technical details, and complications. 3-month postoperative (PostOp) radiological data were analyzed to evaluate the impact of the surgical treatment on radiological parameters. No clinical data (health-related quality-of-life scores) were evaluated, as this was not the subject of this paper.

102 patients met the inclusion criteria. Patients were sequentially split into three groups based on the date of the surgery, First group (1st to 34th case), Second group (35th to 68th case), and Last group (69th to 102nd case). Etiologies are included below (Table 1).

Indications for surgery included sagittal, coronal, or combined malalignment with walking impairment, confirmed by radiological malalignment, including one of sagittal vertical axis (SVA) > 5 cm; pelvic tilt (PT) > 25°; thoracic kyphosis (TK) > 60°, coronal deformity > 20°.

The analyzed demographic variables were age, gender, body mass index (BMI), etiology of the malalignment, comorbidities such as Hypertension, Hypercholesterolemia, Depression, Diabetes, and use of tobacco or alcohol. Past history was recorded looking for a prior lumbar spine surgery.

All the patients had full spine radiographs with the use of the EOS system, supine hyperextension views when possible and MRI with CT scan were done systematically for all the patients. The radiological parameters measured preoperatively and 3 months postoperatively included the curve type classified in the coronal plane according to the SRS–Schwab classification [10], the coronal balance represented by the C7 plumb line in the frontal plane (in relation to the center sacral vertical line), the sagittal vertical axis (SVA), the pelvic tilt, and the pelvic incidence minus lumbar lordosis (PI-LL).

Variables related to the surgical treatment included osteotomy level and type [11], fusion length (number of fused vertebra), iliac fixation, number of Transforaminal Lumbar Interbody Fusion (TLIF) procedures, domino technique, complementary anterior surgery, operative time, estimated blood loss, intra and postoperative complications, and length of hospital stay. The latter parameter was categorized into three time-dependent groups defined as ≤ 13, 14–20, and > 21 days.

Table 1 Deformity etiologies

Diagnosis	*N* (%)
Congenital	3 (3%)
Scheuermann	1 (1%)
Post-traumatic	5 (5%)
Neuromuscular	3 (3%)
Failed-back	61 (60%)
Degenerative	26 (25%)
Ankylosing spondylitis	1 (1%)
Dysplastic spondylolisthesis	2 (2%)

Surgical technique

The patient is installed in a prone position, on four cushions. Spinal cord monitoring is used in the form of transcranial motor evoked potentials, somatosensory evoked potentials, and free running electromyography (EMG) of the lower extremities and evoked EMGs with pedicle screw stimulation.

The operative field is exposed from one level beyond the upper to the lower instrumented vertebra (or the pelvis); a posterior cutaneous midline incision is made. The spine is exposed subperiosteally, going laterally to the transverse processes. Capsulectomies and resection of the inferior articular processes at all levels are performed bilaterally to provide maximum flexibility to the spine. Given that most cases involved fixation to the pelvis, Steinmann pins were inserted to the posterior iliac crest to act as retractors. These may need to be trimmed as they may cause obstruction and capped with protective tubing. A free-hand technique is used to place the pedicle screws including the pelvis if needed, except the vertebra at the osteotomy level. Navigation is usually employed in revision or dysmorphic cases. Given that the selected rods are 6 mm, pre-existing pedicle screws may need to be exchanged to accommodate this.

Both transverse processes of the concerned vertebra are then cut at their bases using an osteotome to expose the lateral wall of the vertebra. A 10-mm Cobb elevator is placed on the lateral wall of the vertebra and moved anteriorly if possible in the subperiosteal plane to the anterolateral quadrant. To retract all the lateral soft tissues, a haemostatic cellulose mesh (Surgicel™) is inserted as a spacer between the bone and the segmental vessels. This is repeated on the other side. Two complete foraminotomies both cephalad and caudal to the pedicles on both sides are made, while protecting the exiting nerve roots with Penfield retractors. A complete laminectomy of the concerned level with partial laminectomy of the level just above is performed, which enables exposure of the pedicles. Both pedicles are than removed exposing the posterior wall. Two transversely oriented osteotomes are then placed above and below each pedicle separated by the distance defined in preoperative planning, which may differ between the right and left side in the case of asymmetrical PSO. Curved osteotomes may be necessary to achieve the wedge-shaped resection. Cancellous bone is removed posterior to anterior on both sides, leaving a 5-mm thickness of the anterior wall to maintain stability. This is the time of most risk of a dural tear. The disc above the osteotomy site is removed if necessary (Schwab type 4), but the anterior wall is left intact. The medial part of the posterior wall is finally removed with an up-angled pituitary rongeur. Most of the bone resection is done from one side.

The correction technique involves cantilevering and compression techniques. A prebent cobalt chrome rod, or more commonly two rods connected by a domino on one side, is applied to the distal screws on the more concave side. The cephalad aspect of the distal rod is left straight and connected to the side-to-side closed domino with the proximal rod contoured to fit the proximal screws. This may be applied directly and smoothly to the proximal screws, controlled with the rod holder (which is tightly grasping the rod at the cephalad aspect). For distal PSOs, e.g., L5, then instead, the proximal rod is lordosed and connected to a short straight distal rod. This may take some adjustments, helped by the stress relaxation of the remaining vertebral body. Further closure of the osteotomy is achieved by compression between the proximal and distal construct through the domino connector. The reduction is assessed during surgery and may be completed by in situ bending, if necessary. The bone-on-bone contact at the osteotomy site should be checked, and in case of a remaining gap, it should be filled with autologous bone graft. The dural sac should be carefully checked, particularly proximally, as kinking may occur with large corrections. The contralateral rod is placed and secured. The fixation is completed by the placement of two crosslink connectors between the two rods, one proximal and one distal. More recently, two satellite rods are used to span the osteotomy site through connection with open side-to-side dominos from the cephalad rod to the caudal rod. The remaining laminae are decorticated with a capener gouge and intact facets are drilled with a burr. There is often an abundance of autologous bone graft but should be used judiciously as pseudoarthroses also occur at non-osteotomised levels. The prepared grafts are placed to cover the maximum surface. Local Vancomycin powder (2 g) is divided into deep and superficial layers and a deep drain is left to prevent epidural hematoma. Frequent readjustment of the self-retainers is helpful to limit muscle damage. Povidone-saline solution washouts are administered at regular intervals.

The patient may stand up for the first time as early as day 2 (D2), with a Thoracic Lumbar Sacral Orthosis and with assistance from a physical therapist; at first, walking is tried without any support; if needed, a walker or a cane is proposed to help the patient adapt to their new posture. An erect full spine radiograph is taken during this event. Patients are discharged once they can walk correctly, and without help, the orthosis is worn for 6 months.

Statistical analyses

Statistical analyses were performed using JMP11 software (SAS Institute, Cary, NC, USA) and STATA14 (StataCorp, College Station, TX, USA). Statistical significance was set at P value < 0.05 (2-tailed).

Patients were sequentially split into three groups based on the date of the surgery: First group (1st to 34th case), Second group (35th to 68th case), and Last group

(69th to 102nd case). Continuous data were described as mean ± standard deviation (SD) if normally distributed, or median and interquartile range (IQR) if not normally distributed. To examine characteristics of the patients assigned to each group, differences in categorical variables were analyzed using Pearson Chi-squared tests, and differences in continuous variables were analyzed using one-way ANOVA, or Kruskal–Wallis test.

Multiple regression analyses were conducted separately for the outcome of interests related to learning curve (operative time, blood loss, and length of hospital stay), while surgical experience (number of cases) was the predictor, and other variables such as demographic, radiographical, and surgical variables were considered as a covariate in the final model. Due to the non-linear nature of learning curve, several curve shapes for the relation between the outcome of interest (operation time, blood loss, and hospital stay) and surgical experience are proposed in the literature [12]. A logarithmic curve was adopted and surgical experience (sequence number of operated patient, SurgEx) is transformed by applying a natural logarithmic transformation (log-SurgEx). Using the log-SurgEx as an independent variable enables observation of the impact of surgical experience, so that 10 cases after the 10th surgery are identical to that of 20 cases after the 20th surgery, and 40 cases after the 40th surgery.

The associations with operative time and blood loss of demographic, radiographical, and surgical variables were evaluated using multivariate linear regression analysis. The final multivariate model was constructed by sequentially adding three blocks of predictors and removing them using a backward elimination method (removal criteria of P value > 0.2): (i) a set of demographic variables (log-SurgEx, age, gender, BMI, comorbidity, past surgery, and diagnosis), (ii) a set of preoperative radiographical variables (Coronal Schwab classification, coronal balance, SVA, PT, and PI-LL), (iii) and a set of surgical variables (osteotomy level, fusion length, Iliac fixation, TLIF, domino technique, two-stage surgery). In the multivariate linear regression models, the residual analyses revealed that the assumptions of normality, linearity, and homoscedasticity were not violated.

A multivariate ordinal logistic regression model with length of hospital stay (3 levels) as independent variable was constructed by putting three clinically important dependent variables including log-SurgEx, age, and fusion length. The results of ordinal logistic regression are presented as the odds ratio of being in a higher level for length of hospital stay. The proportional-odds assumption of ordinal regression was not violated in this model [13].

Results

102 consecutive lumbar PSO patients (69 women, 33 men) were operated in between November 2005 and July 2013. The mean age was 58.7 (SD = 15.3) years. The patients' characteristics in terms of age, gender, BMI, diagnosis, number of comorbidities, past spinal surgery history, and preop radiographic variables are summarized in Table 2. It shows no statistical differences between the three groups.

In the analysis of the surgical treatment data, comparing the three groups, there were no statistically significant differences regarding the osteotomy level, the use of iliac screws, or if the patients had or not a complementary anterior surgery. It was found that the fusion length and the use of TLIF cages decreased, whereas the use of the domino technic and the number of grade 4 osteotomies increased. The last four variables showed statistically significant values, as shown in Table 3.

In the intraoperative outcomes, the mean surgical time decreased by 50 min and the estimated blood loss decreased by 655 ml when comparing the first and the last group. These differences were statistically significant ($P < 0.05$). In addition, there were significant decreases in the hospital length of stay (Table 4).

In the analysis of complications, we found a significant decrease in dural tear occurrence ($P < 0.05$), which were usually treated with suture. Deep infections showed a decreasing trend. We did not find statistical differences between the different groups such as pulmonary complications, deep hematomas, and neurological problems (Table 5).

SVA, PT, and PI-LL showed statistically significant improvement between preoperative and 3-month postoperative values (Table 6).

Multivariate linear regression analysis for operative time and blood loss indicated that improvement in the intraoperative outcome occurs with the increasing of the surgeon's experience.

Decreased operative time was significantly associated with increased surgical experience when adjusted for age, BMI, Schwab curve type, preoperative SVA, and fusion length. The coefficient of Log-SurgEx for operative time was − 41.7 min, meaning that when the surgeon's experience doubles, the operative time decreases by 28.9 (41.7 × log2) minutes. In other words, a surgeon with an experience of 10 lumbar PSOs must complete another 10 PSOs to decrease his operative time by 29 min.

Similar to operative time, intraoperative bleeding was also associated with surgeon's experience when adjusted for past history of surgery, diagnosis, Schwab curve type, preoperative PT and PI-LL, fusion length, and osteotomy level. The coefficient of Log-SurgEx for blood loss was

Table 2 Demographic and preoperative radiological variables

	Total	First series	Second series	Last series	*P*
Demographic variables					
Age: mean (SD)	59 (15)	62 (12)	60 (17)	55 (16)	NS
Gender					
Female: *N* (%)	69 (68)	25 (74)	23 (68)	21 (62)	NS
Male: *N* (%)	33 (32)	9 (26)	11 (32)	13 (38)	
BMI: mean (SD)	25 (4.2)	25 (4.6)	25 (4.0)	26 (4.0)	NS
Diagnosis					NS
Degenerative scoliosis: *N* (%)	26 (25)	10 (29)	9 (26)	7 (27)	
Failed-back: *N* (%)	61 (60)	19 (57)	22 (65)	20 (59)	
Others[a]: *N* (%)	15 (15)	5 (14)	3 (9)	7 (21)	
Comorbidity					NS
0: *N* (%)	29 (28)	15 (44)	7 (21)	7 (21)	
1: *N* (%)	26 (25)	9 (26)	8 (24)	9 (26)	
≥ 2: *N* (%)	47 (46)	10 (29)	19 (56)	18 (52)	
Past surgery					NS
Yes: *N* (%)	74 (73)	23 (69)	25 (74)	26 (75)	
No: *N* (%)	28 (27)	11 (31)	9 (26)	8 (25)	
PreOp radiographical variables					
Coronal Schwab classification[b]					NS
N: *N* (%)	68 (67)	20 (59)	21 (62)	27 (79)	
L: *N* (%)	24 (22)	11 (30)	8 (24)	5 (15)	
D: *N* (%)	10 (11)	3 (11)	5 (15)	2 (6)	
Coronal balance: mean (IQR[c])	23 (11–39)	31 (15–47)	31 (11–51)	16 (9–24)	NS
SVA: mean (SD)	111 (72)	124 (62)	106 (84)	105 (66)	NS
PT: mean (SD)	33 (13)	33 (13)	34 (14)	33 (12)	NS
PI: mean (SD)	55 (17)	53 (14)	53 (17)	59 (19)	NS
PI minus LL: mean (SD)	37 (20)	40 (19)	38 (23)	34 (18)	NS

[a]Others diagnosis includes: Congenital, Scheuermann Disease, post-traumatic, neuromuscular, ankylosing spondylitis, and dysplastic spondylolisthesis

[b]There were no patients with thoracic (without lumbar) curve

[c]Interquartile range

− 405 ml, indicating that when the surgeon's experience doubles, the blood loss decreases by 281 (405 × log2) ml.

Finally, hospital stay also has a correlation with the experience of the surgeon, adjusted by patient's age and fusion length. The coefficient of Log-SurgEx for the hospital stay was 0.549, which means that when the surgeon experience doubles, the odds of hospital stay ≥ 21 days decrease by 0.660 (0.549^log2) times.

Discussion

We have analyzed the learning curve of a single surgeon in one institution regarding lumbar PSO surgical technique, and its impact on the perioperative outcome (excluding clinical data) and complications.

The senior surgeon started his training in pediatric orthopedic (congenital and idiopathic scoliosis) followed by practice of adult degenerative conditions and scoliosis. He was performing all kinds of spinal procedures 4 years before starting the PSO, mainly scoliosis surgeries, adults with use of TLIF cages and Ponte osteotomies when needed, or adolescent idiopathic: initially, anterior approaches were done, and later on, almost only posterior approaches became the rule, with the use of all pedicle screws construct and the development of the free-hand technique, that enabled important corrections. The number of scoliosis surgeries done prior to the PSO learning curve was around 300 cases. Mastering the posterior surgery for scoliosis in terms of anatomy recognition, screws' insertion, and bleeding management is an important prerequisite prior to starting the PSO; as it permits the acquisition of some automatisms, enabling the surgeon to focus mainly on the new and risky technique that he is trying to learn.

The results of the current study showed a progressive improvement of the surgeon's experience over time in both

Table 3 Comparison of the surgical data for the three studied groups

	Total	First series	Second series	Last series	*P*
Type of surgical treatment					
Osteotomy level					NS
L1, 2, 3: *N* (%)	31 (30)	14 (41)	11 (32)	6 (18)	
L4: *N* (%)	62 (61)	19 (56)	21 (62)	22 (64)	
L5, S1: *N* (%)	9 (9)	1 (3)	2 (6)	6(18)	
Fusion length: median (IQR[a])	9 (7–12)	11 (9–5)	10 (6–13)	8 (6–10)	0.008
Iliac screw					NS
Yes	87 (73)	29 (85)	30 (88)	28 (82)	
No	15 (27)	5 (15)	4 (12)	6 (18)	
TLIF					0.016
No TLIF 0: *N* (%)	55 (53)	14 (39)	16 (48)	25 (72)	
1: *N* (%)	23 (23)	8 (24)	7 (21)	8 (23)	
≥ 2: *N* (%)	24 (23)	12 (36)	11 (30)	1 (3)	
Osteotomy grade					0.035
3	64 (37)	28 (33)	24 (41)	12 (21)	
4	38 (26)	6 (12)	10 (19)	22 (37)	
Domino technique					0.049
Yes	78 (73)	11(33)	26 (81)	30 (91)	
No	20 (27)	22 (67)	6 (19)	3 (9)	
Complementary anterior surgery					NS
Yes	8 (8)	2 (6)	2 (6)	4 (12)	
No	94 (92)	32 (94)	32 (94)	30 (88)	

[a]Interquartile range

Table 4 Comparison of the operative outcome for the three studied groups

	Total	First series	Second series	Last series	*P*
Operative time (min): mean (IQR*)	240 (210–280)	270 (240–352)	240 (180–285)	220 (197–240)	0.001
Blood loss (ml): mean (IQR[a])	2000 (1400–2800)	2255 (1762–3625)	2100 (1350–2900)	1600 (1300–2200)	0.041
Hospital stay					0.019
≤ 13 days	39 (38)	9 (27)	11 (29)	19 (58)	
14 ≤ but ≤ 20 days	37 (37)	11 (33)	17 (50)	9 (27)	
≥ 21 days	26 (25)	14 (40)	7 (21)	5 (15)	

[a]Interquartile range

the surgical strategy and the techniques used for the osteotomy, which resulted in a significant decrease of the complications rate and a shorter hospital stay. The population of this study was split into three groups based on the date of the surgery, and the demographic data of each series did not show significant differences between the groups, which enabled us to compare the different surgical strategies, techniques used, complications, and radiological outcomes with minimal bias. Only 3-month X-rays were added to show a globally stable immediate postoperative radiological outcome over the course of time. Longer radiological and clinical evaluation will be part of another paper in the future.

Regarding the surgical strategy, less levels of instrumentation and less TLIF procedures were performed with time. The reduced TLIFs were probably related to the increase of grade 4 osteotomy [11], compared to the grade 3 that was mainly done before, which made the surgical procedures globally less invasive; Actually, grade 4 includes resection of the cranial disc with the osteotomy, which avoid putting an interbody cage proximally (either by a posterior or an additional anterior approach); we consider avoiding the latter step a gain of time and help in decreasing the blood loss, this is why we consider the grade 4 less invasive than the grade 3, in terms of morbidity, despite the fact that grade 4 resects more than grade 3. The fact of adding a cage proximally to a grade 3 to avoid future mechanical complications puts an additional non-negligible step to the surgery.

Table 5 Complications of the series

	Total	First series	Second series	Last series	*P*
Intraoperative					
Dural tear					.025
Yes	12	8	1	3	
No	90	26	33	31	
Others					
Intraoperative death	1	0	0	1	NS
Operation incomplete due to severe bleeding	1	1	0	0	NS
Postoperative					
Hematoma					NS
Yes	4	0	2	2	
No	98	34	32	32	
Deep infection					NS
Yes	9	4	3	2	
No	93	30	31	32	
Others					
Paralysis	2	2	0	0	
Pulmonary embolism	1	1	0	0	NS

Table 6 Comparison of the postoperative radiological outcome for the three studied groups

Postop radiographical data (3 months after operation)	Total	First series	Second series	Last series	*P*
Coronal balance: mean (IQR[a])	9 (2–25)	14 (0–33)	10 (0–20)	5 (0–9)	NS
SVA: mean (SD)	28 (35)	24 (27)	21 (39)	40 (37)	NS
PT: mean (SD)	16 (12)	15(13)	17 (13)	18 (9)	NS
PI minus LL: mean (SD)	− 1(14)	− 3(16)	− 2(17)	3 (9.1)	NS

[a]Interquartile range

This tendency of selecting less invasive surgical option reflects the surgeon's improvement with the surgical strategy potentially linked to a better assessment of multiples variables such as age, osteoporosis, sagittal and coronal balance, level of osteotomy, and the presence of a kyphotic thoracic curve. More L5 or S1 PSOs, which are more complicated and risky, were performed in the later group, which may correlate with a better surgeon's confidence related to skills' improvement. L5 PSO [14] is done mainly in revision cases (postoperative flatback deformity) when an important amount of correction is needed given the big size of the L5 vertebra, or if the apex of the deformity, i.e., the area to be targeted to get the best correction with a harmonious lordosis is at the L4 L5 or the L5 level. In addition, L5 PSO is indicated in case of distal junctional kyphosis below a construct stopping at L5. S1 PSO [15] is done in case of revision of dysplastic spondylolisthesis with severe lumbosacral kyphosis, where the apex of the deformity is the proximal sacral area.

In the perioperative data, the learning curve demonstrated significantly decreased operation time, decreased blood loss, and decreased dural tears, which was observed after multivariate adjustment for different demographic or radiological parameters. Similarly, in the postoperative period, hospital stay significantly decreased over the time.

Global improvement in the learning curve for lumbar PSO technique is the result of the addition of specific improvements of multiple variables surrounding the patient's procedure, in the preoperative period with the surgical strategy, in the peroperative period with the surgical skills, and in the postoperative period with the hospital stay and the follow-up course. No paper in the literature was found describing the learning curve for lumbar PSO's. The literature either describes the surgical technique, outcomes and complications of cohorts, or retrospective series of PSO's [16–18], which are consistent with our results, or describes the learning curves for different types of spinal surgeries such as scoliosis, minimal invasive procedures, endoscopic spinal surgery, anterior thoracolumbar tumor resections, or anterior cervical fusion [19–25].

One important element in the learning curve is the surgical strategy. In other words, the patient's selection and the type of surgery that the patient needs, according to their global status and clinical and radiological data, are of most importance. In addition, all this process starts in the clinic where the surgeon collects all available information from the medical history, the physical examination, a thorough radiological study evaluating the sagittal and coronal alignment, and the MRI for the assessment of the degree of nerves compression and disc hydration. After the PSO is chosen as the correction technique, strategy should focus on achieving the surgery with the shortest possible construct, and avoiding any additional surgeries (single approach in a single session). Final target of the surgery with the PSO would be to achieve the spinopelvic ideal alignment as published by Schwab et al. [26], with an SVA < 5 cm, PT < 20°, and LL = PI ± 9 degrees.

The surgeon's preference with the use of the domino for the reduction technique increased significantly over the years ($P < 0.05$) with almost 100% of the patients treated with this same technique currently, so that the load is spread on all the proximal and distal screws together while doing the compression at the level of the osteotomy site during reduction. Applying satellite rods at the osteotomy level [27], with a 4-rod configuration, gives the instrumentation more rigidity, to decrease the rate of mechanical problems such as rod breakage and non-union over the long fusion period. The OARM navigation system [28] (which has its own learning curve) probably decreases the time and risks in very complex revision and congenital cases. Use of navigation started for us in 2009, it enabled the management of very complex cases with multiple revisions where bony landmarks are gone, or in severe deformities with difficult screws insertion, or in case of high thoracic osteotomies to control the cut at the anterior cortex. However, we do not think that it impacted the results as an improvement of the learning curve of PSO's compared to the classical technique without navigation; it rather helped us to push further the indications' limits in specific cases in a safe manner.

The surgical technique improvement came through technical refinements that occurred over the time, with meticulous dissection with the electric cautery, regular hemostasis with the bipolar, never leaving an ongoing bleeding, use of hemostatic agents, quick insertion of the screws with the free-hand technique, and gauzes packing in non-working areas; bone wax is avoided as much as possible for better bone healing and used only for punctual bone bleeding. Therefore, globally, less amount of bleeding decreases its management time, subsequently decreasing the operative time. The significant improvement in decreasing operative time and blood loss also reflects improvement of the learning curve of the surgical team, including the anesthesia management, although this is difficult to demonstrate.

Decrease of hospital stay may be related to the decrease in operative time, decreased blood loss, and lesser dissection that probably accelerate the recovery, but it also may indicate improvements and changes of the postoperative management of the surgeon, physiotherapists, and nurses.

Conclusion

A detailed learning curve for lumbar pedicle subtraction osteotomy technique is described based on a single surgeon's practice providing useful information for spine surgeons who are willing to embrace this technique. Furthermore, the evolution of this technique promotes others to potentially start their experience at a higher point along this curve.

This study demonstrated that decreasing operative time and blood loss becomes increasingly complicated, as it is proportional to doubling the number of cases; therefore, it is easy to double the number of surgeries when 2 only were made to reach a 29-min improvement in timing, but it is more difficult and challenging to get the same improvement when 20 cases have been performed as 20 more will be needed to get the same amount of improvement.

Analysis of the learning curve in surgery helps us to realize how the progressive experience plays an important role in mastering the technique, especially in complex procedures like the PSO, where every detail is important and operative time matters. Hence, PSOs should be performed only in referral centers and only by 1–2 spinal surgeons within the same institution, for the purpose of accumulating experience over time.

Compliance with ethical standards

Conflict of interest There are no conflicts of interest for this paper.

References

1. Schwab F, Lafage V, Farcy JP, Bridwell K, Glassman S, Ondra S, Lowe T, Shainline M (2007) Surgical rates and operative outcome analysis in thoracolumbar and lumbar major adult scoliosis: application of the new adult deformity classification. Spine 32:2723–2730. https://doi.org/10.1097/BRS.0b013e31815a58f2
2. Lafage V, Schwab F, Patel A, Hawkinson N, Farcy JP (2009) Pelvic tilt and truncal inclination: two key radiographic parameters in the setting of adults with spinal deformity. Spine 34:E599–606. https://doi.org/10.1097/BRS.0b013e3181aad219
3. Liu S, Schwab F, Smith JS, Klineberg E, Ames CP, Mundis G, Hostin R, Kebaish K, Deviren V, Gupta M, Boachie-Adjei O, Hart RA, Bess S, Lafage V (2014) Likelihood of reaching minimal clinically important difference in adult spinal deformity: a comparison of operative and nonoperative treatment. The Ochsner journal 14:67–77
4. Been E, Barash A, Marom A, Kramer PA (2010) Vertebral bodies or discs: which contributes more to human-like lumbar lordosis? Clin Orthop Relat Res 468:1822–1829. https://doi.org/10.1007/s11999-009-1153-7

5. Glassman SD, Bridwell K, Dimar JR, Horton W, Berven S, Schwab F (2005) The impact of positive sagittal balance in adult spinal deformity. Spine 30:2024–2029
6. Berjano P, Aebi M (2015) Pedicle subtraction osteotomies (PSO) in the lumbar spine for sagittal deformities. Eur Spine J 24(Suppl 1):S49–57. https://doi.org/10.1007/s00586-014-3670-7
7. Bridwell KH, Lewis SJ, Edwards C, Lenke LG, Iffrig TM, Berra A, Baldus C, Blanke K (2003) Complications and outcomes of pedicle subtraction osteotomies for fixed sagittal imbalance. Spine 28:2093–2101. https://doi.org/10.1097/01.BRS.0000090891.60232.70
8. Buchowski JM, Bridwell KH, Lenke LG, Kuhns CA, Lehman RA Jr, Kim YJ, Stewart D, Baldus C (2007) Neurologic complications of lumbar pedicle subtraction osteotomy: a 10-year assessment. Spine 32:2245–2252. https://doi.org/10.1097/BRS.0b013e31814b2d52
9. Maier S, Smith JS, Schwab F, Obeid I, Mundis G, Klineberg E, Hostin R, Hart R, Burton D, Boachie-Adjei O, Gupta M, Ames C, Protopsaltis T, Lafage V, International Spine Study G (2014) Revision surgery after three-column osteotomy in 335 adult spinal deformity patients: inter-center variability and risk factors. Spine. https://doi.org/10.1097/brs.0000000000000304
10. Schwab F, Ungar B, Blondel B, Buchowski J, Coe J, Deinlein D, DeWald C, Mehdian H, Shaffrey C, Tribus C, Lafage V (2012) Scoliosis Research Society—Schwab adult spinal deformity classification: a validation study. Spine 37:1077–1082. https://doi.org/10.1097/BRS.0b013e31823e15e2
11. Schwab F, Blondel B, Chay E, Demakakos J, Lenke L, Tropiano P, Ames C, Smith JS, Shaffrey CI, Glassman S, Farcy JP, Lafage V (2014) The comprehensive anatomical spinal osteotomy classification. Neurosurgery 74:112–120. https://doi.org/10.1227/neu.0000000000000182o **(discussion 120)**
12. Ramsay CR, Grant AM, Wallace SA, Garthwaite PH, Monk AF, Russell IT (2001) Statistical assessment of the learning curves of health technologies. Health Technol Assess 5:1–79
13. Fu V (1999) Estimating generalized ordered logit models. Stata Tech Bull 8(44)
14. Alzakri A, Boissiere L, Cawley DT, Bourghli A, Pointillart V, Gille O, Vital JM, Obeid I (2017) L5 pedicle subtraction osteotomy: indication, surgical technique and specificities. Eur Spine J. https://doi.org/10.1007/s00586-017-5403-1
15. Bodin A, Roussouly P (2015) Sacral and pelvic osteotomies for correction of spinal deformities. Eur Spine J 24(Suppl 1):S72–82. https://doi.org/10.1007/s00586-014-3651-x
16. Kim KT, Lee SH, Suk KS, Lee JH, Jeong BO (2012) Outcome of pedicle subtraction osteotomies for fixed sagittal imbalance of multiple etiologies: a retrospective review of 140 patients. Spine 37:1667–1675. https://doi.org/10.1097/BRS.0b013e3182552fd0
17. Dickson DD, Lenke LG, Bridwell KH, Koester LA (2014) Risk factors for and assessment of symptomatic pseudarthrosis after lumbar pedicle subtraction osteotomy in adult spinal deformity. Spine 39:1190–1195. https://doi.org/10.1097/BRS.0000000000000380
18. Savage JW, Patel AA (2014) Fixed sagittal plane imbalance. Global Spine J 4:287–296. https://doi.org/10.1055/s-0034-1394126
19. Ahn J, Iqbal A, Manning BT, Leblang S, Bohl DD, Mayo BC, Massel DH, Singh K (2015) Minimally invasive lumbar decompression-the surgical learning curve. Spine J. https://doi.org/10.1016/j.spinee.2015.07.455
20. Gang C, Haibo L, Fancai L, Weishan C, Qixin C (2012) Learning curve of thoracic pedicle screw placement using the free-hand technique in scoliosis: how many screws needed for an apprentice? Eur Spine J 21:1151–1156. https://doi.org/10.1007/s00586-011-2065-2
21. Mayo BC, Massel DH, Bohl DD, Long WW, Modi KD, Singh K (2016) Anterior cervical discectomy and fusion—the surgical learning curve. Spine. https://doi.org/10.1097/BRS.0000000000001588
22. Ray WZ, Schmidt MH (2016) Thoracoscopic vertebrectomy for thoracolumbar junction fractures and tumors: surgical technique and evaluation of the learning curve. Clin spine Surg 29:E344–350. https://doi.org/10.1097/BSD.0b013e318286fa99
23. Ryu KJ, Suh SW, Kim HW, Lee DH, Yoon Y, Hwang JH (2016) Quantitative analysis of a spinal surgeon's learning curve for scoliosis surgery. Bone Jt J 98-B:679–685. https://doi.org/10.1302/0301-620x.98b5.36356
24. Samdani AF, Ranade A, Saldanha V, Yondorf MZ (2010) Learning curve for placement of thoracic pedicle screws in the deformed spine. Neurosurgery 66:290–294. https://doi.org/10.1227/01.neu.0000363853.62897.94 **(discussion 294-295)**
25. Wu XB, Fan GX, Gu X, Shen TG, Guan XF, Hu AN, Zhang HL, He SS (2016) Learning curves of percutaneous endoscopic lumbar discectomy in transforaminal approach at the L4/5 and L5/S1 levels: a comparative study. J Zhejiang Univ Sci B 17:553–560. https://doi.org/10.1631/jzus.B1600002
26. Schwab F, Patel A, Ungar B, Farcy JP, Lafage V (2010) Adult spinal deformity-postoperative standing imbalance: how much can you tolerate? An overview of key parameters in assessing alignment and planning corrective surgery. Spine 35:2224–2231. https://doi.org/10.1097/BRS.0b013e3181ee6bd4
27. Hyun SJ, Lenke LG, Kim YC, Koester LA, Blanke KM (2014) Comparison of standard 2-rod constructs to multiple-rod constructs for fixation across 3-column spinal osteotomies. Spine 39:1899–1904. https://doi.org/10.1097/BRS.0000000000000556
28. Vital JM, Boissiere L, Bourghli A, Castelain JE, Challier V, Obeid I (2015) Osteotomies through a fusion mass in the lumbar spine. Eur Spine J 24(Suppl 1):S107–111. https://doi.org/10.1007/s00586-014-3657-4

Affiliations

Anouar Bourghli[1] · Derek Cawley[2] · Felipe Novoa[2] · Manuela Rey[2] · Abdulmajeed Alzakri[2] · Daniel Larrieu[2] · Jean-Marc Vital[2] · Olivier Gille[2] · Louis Boissiere[2] · Ibrahim Obeid[2]

✉ Anouar Bourghli
anouar.bourghli@gmail.com

[1] Orthopedic and Spinal Surgery Department, Kingdom Hospital, P.O. Box 84400, Riyadh 11671, Saudi Arabia

[2] Orthopedic Spinal Surgery Unit 1, Bordeaux Pellegrin Hospital, Bordeaux, France