Single Level Proximal Thoracic Pedicle Subtraction Osteotomy for Fixed Hyperkyphotic Deformity: Surgical Technique and Patient Series

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BACKGROUND: Thoracic hyperkyphosis can display pathological deterioration, resulting in either hyperlordotic cervical compensation or sagittal malalignment. Various techniques have been described to treat fixed malalignment. Pedicle subtraction osteotomy (PSO) is commonly used in the lumbar spine and frequently limited to the distal thoracic spine. This series focuses on the surgical specificities of proximal thoracic PSO, with clinical and radiological outcomes.

OBJECTIVE: To report the surgical specificities and assess the clinical and radiological outcomes of proximal thoracic osteotomies for correction of rigid kyphotic deformities.

METHODS: This is a retrospective review of 10 consecutive patients who underwent single level proximal thoracic PSO (T2-T5). Preoperative and postoperative full-body EOSTM radiographs, perioperative data, and complications were recorded. The surgical technique and its nuances were described in detail.

RESULTS: Patients had mean age of 41.8 yr and 50% were female. The technique provided correction of segmental and global kyphosis, 26.6° and 29.5°, respectively. Patients reported reciprocal reduction in C2-C7 cervical lordosis (37.6°-18.6°, $P < .001$), significantly correlating with the reduction of thoracic hyperkyphosis ($R = 0.840$, $P = .002$). Mean operative time was 291 min, blood loss 1650 mL, and mean hospital stay was 13.8 d. Three patients reported complications that were resolved, including 1 patient who was revised because of a painful cross link. There were no neurological complications, pseudarthroses, instrumentation breakage, or wound infections at a minimum of 2-yr follow-up.

CONCLUSION: Proximal thoracic PSO can be a safe and effective technique to treat fixed proximal thoracic hyperkyphosis leading to kyphosis reduction and craniocervical relaxation.

KEYWORDS: Proximal thoracic osteotomy, Pedicle Subtraction Osteotomy, PSO

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Thoracic hyperkyphosis can display deterioration for reasons such as increasing age, osteoporosis, disc degeneration, etc resulting in either hyperlordotic cervical compensation to maintain horizontal gaze or sagittal malalignment to minimize the excruciating pain of nerve compression. Among the

various techniques utilized to treat patients with spinal malalignment, pedicle subtraction osteotomy (PSO) is a robust operative technique to correct rigid deformities, achieving up to 40° of focal lordosis when performed in the lumbar spine.^{1,2} A thoracic spine PSO, however, is significantly more challenging.³ Even within the thoracic spine, a proximal thoracic osteotomy is considered to be much more technically demanding than a distal thoracic osteotomy, primarily from the increased risk of spinal cord lesions in the proximal thoracic spine.

Recent reports have advocated for the use of 3-column osteotomy in the thoracic spine. Zeng et al¹ investigated the radiographic and clinical outcomes of upper thoracic osteotomies

ABBREVIATIONS: CL, cervical lordosis; GT, global tilt; LL, lumbar lordosis; LLI, lumbar lordosis index; PI, pelvic incidence; PT, pelvic tilt; PSO, pedicle subtraction osteotomy; pVCR, posterior vertebral column resection; SD, standard deviation; SPO, Smith-Petersen osteotomy; SVA, sagittal vertical axis

FIGURE 1. Patient is installed in prone position with the head fixed by a Mayfield frame (Integra LifeSciences). Neuromonitoring for reduction maneuvers is mandatory and navigation for proximal screw positioning can be very useful.

(6 PSOs vs 7 vertebral column resections) in adult patients with a congenital or post-tuberculosis kyphosis (mean age: 30 yr). Their study demonstrated that satisfactory results were attainable when correcting focal kyphosis in the upper thoracic spine, concluding that PSO was the preferred operative technique. While PSOs were as effective in correcting the focal kyphosis in the upper thoracic spine as vertebral column resections, PSOs had fewer complications. Theologis et al² reported the results of lower cervical and upper thoracic osteotomies after 2 yr. Their study,² which included 12 patients with proximal thoracic PSOs, recommended the use of 3-column osteotomies to restore sagittal alignment and improve the quality of life in patients with cervicothoracic kyphosis.³ Detailed descriptions of the surgical technique have not been well documented heretofore.^{4,5}

METHODS

Study Design and Size

This is a retrospective review of 10 consecutive patients who underwent proximal thoracic PSO with a minimum of 2-yr follow-up.

Setting and Data Source

Patients were included from a single center, and operated on by the same surgeon (IO) between December 2009 and February 2013. Data collected included perioperative details, sagittal spinal parameters, and all complications. Patients were followed up at 3, 6, and 12 mo after surgery in the clinic.

Because of the retrospective nature of the study, it was approved as exempt research by the Institutional Review Board. All patients were explained about the surgery and participating in the study and they provided informed consents. The patient in Figure 1 consented to publication of his image.

Participants

Patients who presented with a symptomatic, severe, and rigid thoracic hyperkyphosis were included in the study. These were the first 10 consecutive cases in the aforementioned time period. All patients in this study presented with intractable back and neck pain, the primary clinical manifestation of symptomatic and positive sagittal malalignment. All patients had been initially conservatively treated including physiotherapy and with oral analgesia. A thoracic PSO was carried out only when other, less aggressive osteotomies (eg, a Smith-Petersen osteotomy [SPO]) were not feasible from the lack of sagittal curve flexibility.⁶ All patients included were neurologically intact preoperatively (Frankel E). The mean age was 41.8 yr (15-76). Mean follow-up was 33.60 mo (24-54). Preoperatively, patients underwent thorough historical and neurological examinations. Additionally, patients underwent regional and global radiographic spinal alignment analysis via standing full-body EOSTM radiographs (EOSTM Imaging, Paris, France).⁷

Radiographic Variables and Clinical Outcomes

Focal sagittal kyphosis was assessed using the Cobb angle between the superior endplate of the vertebra above the PSO level and the inferior endplate of the vertebra below the PSO level. Regional radiographic measurements of sagittal alignment included lower cervical lordosis (CL; C2-C7 Cobb angle), upper CL (Occiput-C2 "C0-C2" Cobb angle: the angle between the McGregor line and the inferior endplate of C2), C7 Slope, thoracic kyphosis (T1-T12 Cobb angle), and lumbar lordosis (LL: L1-S1 Cobb angle). The pelvic parameters measured included pelvic incidence (PI) and pelvic tilt (PT). Global radiographic measurements included sagittal vertical axis (SVA), global tilt (GT), and lumbar lordosis Index (LLI).⁷ Radiographic measurements were performed using SpineView, a validated software (Laboratory of Biomechanics, ENSAM ParisTech, Paris, France⁸). Supine lateral scoliosis radiographs, with the patient positioned over a bolster, were routinely performed to assess the rigidity of the kyphosis. Oswestry Disability Index scores were collected at baseline and 2-yr follow-up.

Surgical Technique

Each patient was carefully placed in the prone position with the head fixed in a Mayfield frame (Integra LifeSciences, Plainsboro, New Jersey). The kyphosis warrants positioning considerations, including placing the thoracic bolsters slightly more distally to accommodate the shape of the proximal thoracic spine. Furthermore, the head position will most likely lie below the level of the chest and adequate space beyond the head and below the face is important. This may be helped by a slight reverse Trendelenburg position. The surgical procedure was performed with intraoperative neuromonitoring (motor and somatosensory evoked potentials; Figure 1). Systolic blood pressure of greater than 100 mm Hg was rigorously maintained throughout each case to ensure adequate spinal cord perfusion. After posterior approach, midline paravertebral exposure and facetectomies were performed, and O-arm (Medtronic Inc, Dublin, Ireland) intraoperative navigation images were obtained. While pedicle screws were inserted mostly using a freehand technique for the vertebrae caudal to the PSO level, proximal thoracic and cervical pedicles tend to be more difficult in the presence of severe kyphosis; thus, accuracy is improved with navigation. O-arm-based navigation is also beneficial during this procedure for placing implants in old fusion masses or abnormal osseous morphology and for identifying the limit of the depth of bone resection during the osteotomy procedure.

FIGURE 2. Extrapleural rib exposure. In this case, 2 ribs were removed to allow a proper exposure of the lateral wall on the convex side.

FIGURE 3. Lateral wall exposures after rib head resection.

The posterior aspect of the ribs at the level of the vertebra undergoing the PSO was exposed through the same incision so as to remove approximately 5 cm of rib on either side. Remaining extrapleural is difficult, and frequently a small pleural perforation can occur. A chest radiograph may be performed in the recovery room postoperatively and a chest drain may be inserted if evident radiographically. Bilateral and partial costectomies (Figure 2) allow good visualization of the vertebral body's lateral walls and the posterior vertebral wall. This large resection (the removal of 5 cm of rib including the rib head) will avoid spinal cord mobilization maneuvers during the osteotomy procedure (Figure 3). It is best to remove each rib section en bloc as the free rib end (once cut laterally) can be mobilized

to aid hemostasis as it is dissected medially, with the aid of a Penfield dissector from the costotransverse and costovertebral joints.

Exposure of the lateral vertebral body wall was carried out bilaterally with a sharp Cobb dissector and a cellulose mesh (Surgicel™; Ethicon, Summerville, New Jersey) was applied to the segmental vessels, which lie at the equator of the vertebra. Vertebral body resection is made from the lateral wall, through the pedicles as the spinal canal is finally exposed. After posterior element and pedicle resections, the lateral vertebral body wall cuts were made with straight osteotomes in a precise wedge, based on the desired degree of closure. The distal cut is made below the pedicle and the proximal cut is just above the inferior endplate of the cephalad vertebra to the osteotomy level (ie, Schwab osteotomy type 4, Figure 4). The resection depth (apex of the wedge) is controlled by intra-operative navigation to ensure that the wedge apex is 1 cm before the anterior vertebral body wall. No temporary rod was placed during the osteotomy. Although the anterior wall can be quite thin, the Mayfield frame (Integra LifeSciences) and wedge apex's anterior limit provide enough stability during the procedure. The posterior wall is removed with 45° angulated pituitary forceps. The forceps' jaws are opened outside the vertebra, and the upper jaw is inserted carefully between the anterior dura and the posterior wall. Then the bone is pushed anteriorly into the vertebra. Removing the upper intervertebral disc allows a higher degree of correction and increases the probability of fusion (bone-to-bone contact). In the disc space, the same posterolateral technique was used to approach the resection of the posterior annulus and disc.

Final correction was achieved by simultaneous internal and external maneuvers. An experienced operator (outside of the surgical field) who is familiar with the workings of the Mayfield frame (Integra LifeSciences) is best placed so that they can steadily maintain the Mayfield frame as an assistant loosens the table attachments. Two precontoured cobalt chrome rods connected by a domino are applied across the PSO site. The head and neck are then extended to create closure of the osteotomy and telescoping of the rods (Figure 5). If the kyphosis is such that the proximal and distal rods do not meet before correction, then the rods are applied distally and as the head is lifted, the rods are guided into the proximal screws (cantilever bending). These combined maneuvers allow posterior closing of the wedge site, ultimately leading to a smooth correction while avoiding spinal cord trauma at the osteotomy level (Figure 6). Compression on the convex site of a coronal deformity allows for an asymmetric closure and a coronal plane correction if needed (Figure 7). During the correction maneuver, it is very important to pay attention to neuromonitoring; signal changes must guide the surgeon to stop or alter the technique and correction. Once correction is achieved, the Mayfield frame (Integra LifeSciences) was fixed in place before starting decortication and wound closure. A postoperative Philadelphia cervical collar was worn for 3 mo by all patients. Secondary surgery to perform an anterior graft by thoracotomy was not necessary for any patient.

Statistical Analysis Methods

Demographic, surgical, and radiographic parameters were evaluated using descriptive statistics of means and standard deviations (SD). There was no loss of follow-up. Frequency analysis was utilized to report the incidences of complications. Pre- and postoperative parameters were compared using the Student's paired t-test for continuous variables. Correlation analyses between the parameters were evaluated by the Pearson co-efficient. A $P < .05$ was considered statistically significant.

RESULTS

Participants and Descriptive Data

Patient population (Table 1): 10 patients with a minimum of 2 yr of follow-up (mean: 33.6 mo), and mean age of 40.7 yr (SD = 24). These patients suffered from the following pathologies: neurofibromatosis kyphoscoliosis (n = 4, all < 35 yr), proximal junctional kyphosis (n = 3), post-traumatic kyphosis (n = 2), and degenerative kyphoscoliosis (n = 1). Seven patients were primary cases. The 3 revision patients presented with proximal junctional kyphosis and fusion masses at the kyphotic level. PSO was mostly performed at T4 (n = 7), followed by T5 (n = 2), and T1 (n = 1).

Outcome Data and Main Results

Operative data and complications (Table 2): on average, the surgical time was 291 min (range: 210-350 min), the blood loss was 1650 mL (range: 800-3200 mL), and the hospital stay was 13.8 d (range: 7-29 d). Five complications were reported. Two patients had postoperative hemothoraces that required drainage, 1 patient had postoperative gastrointestinal bleeding that resolved spontaneously, and 1 patient had an asymptomatic rod breakage that did not require revision. One structural complication from a painful cross link under the skin was also reported and removed 3 mo after the surgery. There were no transient or permanent neurological complications, no pseudarthroses, and no wound infections at the minimum of 2-yr follow-up.

FIGURE 7. A final compression can be realized on the domino on the opposite site of the coronal deformity. It allows a safe asymmetric closure and coronal plane correction if needed. This method allows distributing the compression forces on all the implants to avoid screw pullout.

Clinical outcomes included Oswestry Disability Score which changed from a mean of 40 (SD = 22, range 2-66) preoperatively to a mean of 28 (SD = 19, range 2-52) postoperatively.

Radiological Evaluation

The radiographic results are reported in Table 3. Preoperatively, the mean segmental kyphosis was 58.30° , for a mean thoracic kyphosis of 83.1° . Hyperkyphosis had no impact on global spinal malalignment (mean SVA: -11.8 mm, mean GT: 17.1°) or pelvic retroversion with a mean PT of 20.3° , with a mean PI of 85.5° . The compensatory mechanisms involved were mainly present in the lower cervical spine as hyperlordosis (C2-C7 CL: -37.6° , C1-C7 CL: 69.2°). The C7 slope was 55.4° , and there was no mismatch between PI and LL as measured by PI-LL (-0.7°) or LLI (1.0°).

Postoperatively, segmental kyphosis and thoracic kyphosis both significantly decreased by 26.6° and 29.5° , respectively (58.3° vs 31.7° , $P < .001$; 83.1° vs 53.6° , $P < .001$). A reciprocal reduction in C2-C7 CL (37.6° vs 18.6° , $P < .001$) and C1-C7 lordosis (69.2° vs 48.7° , $P = .008$) was also noted. There was no significant difference between pre- and postalignment in terms of upper CL (C0-C2), LL, pelvic parameters, and global alignment. There was significant and positive correlation between the reduction of thoracic kyphosis and the reduction of C1-C7 lordosis ($R = 0.840$, $P = .002$).

Pre- and postoperative Oswestry Disability Index scores revealed improvements in the majority of the patients (Table 4).

DISCUSSION

The technique described in this study has several advantages. The use of the Mayfield frame (Integra LifeSciences) and the preservation of the anterior vertebral wall provide good stability during the resection and correction maneuvers. Thus, the use of temporary rods is not necessary and may prevent rotational movements during correction. The rib resection affords adequate visibility to allow wedge resection of the vertebral body. The Schwab type 4 PSO is particularly relevant in the proximal thoracic spine given the smaller thoracic vertebra and accessible disc. The cancellous bone quality in this region allows generous bone healing potential. Furthermore, the wedge closure does not require a large effort during the correction maneuvers. While the posterior wedge closes, there is a slight opening across the resected disc space, which allows for a larger angular correction with a smaller posterior shortening, while avoiding dural kinking; this can explain the larger correction magnitude in this series. Furthermore, the use of simultaneous internal and external maneuvers allows for a progressive and safe correction, thus diminishing potential for neurological deficits. Finally, the

TABLE 1. Age, Gender, Local Kyphosis, Revisions and Indication for Surgery for all Patients

Patient	Age/gender	Local kyphosis pre-op	Previous surgery	PSO level	Indication
1	25/F	47°	Yes	T5	PJK
2	69/F	56°	Yes	T4	PJK
3	76/M	32°	No	T2	DJK
4	32/M	60°	No	T4	NF
5	17/F	45°	No	T4	NF
6	15/F	98°	No	T4	NF
7	17/M	89°	No	T5	NF
8	66/F	61°	No	T4	Trauma
9	32/M	30°	Yes	T4	PJK
10	58/M	65°	No	T4	Trauma
Total	Mean 40.7/50% F	58.3°	30%		

PJK, proximal junctional kyphosis; DJK, Distal junctional kyphosis; NF, Neurofibromatosis.

TABLE 2. Operative Data and Complications for all Patients

Patient	Local kyphosis correction	OR time/min	Osteotomy level	UIV-LIV	Blood loss/mL	Complications
1	24	245	T5	C7-L2	1000	No
2	23	350	T4	C6-Pelvis	800	Cross link removal
3	29	340	T2	C7-T6	2400	Hemothorax
4	20	280	T4	C7-L1	3200	GI Bleeding
5	30	340	T4	C7-T10	1400	Hemothorax
6	33	300	T4	T1-L1	2600	1 rod breakage
7	32	210	T5	T1-L1	900	No
8	34	240	T4	T1-T10	1700	No
9	23	260	T4	C7-L2	800	No
10	18	345	T4	T1-T7	1700	No

OR, operating room; UIV-LIV, Upper Instrumented Vertebra/Lowest Instrumented Vertebra.

TABLE 3. Radiographic Evaluation

	Preop		Postop		Change		P
	Mean	SD	Mean	SD	Mean	SD	
Local kyphosis (°)	58.3	22.1	31.7	20.7	-26.6	5.7	.000
TK (°)	83.1	18.0	53.6	15.0	-29.5	8.9	.000
C0C2 (°)	31.6	13.8	30.5	12.4	-1.1	9.8	.730
C1C7 (°)	69.2	38.2	48.7	31.0	-20.5	19.3	.008
C2C7 (°)	37.6	32.2	18.6	25.0	-19.0	15.6	.004
C7 slope (°)	55.4	18.4	34.7	16.3	-20.7	9.5	.000
C7 Tilt (°)	17.1	16.4	15.4	10.4	-1.7	10.5	.621
PI (°)	58.6	16.8	57.9	17.2	0.6	1.8	.290
PT (°)	20.3	7.9	19.7	7.9	-0.6	2.3	.418
LL (°)	59.2	13.7	59.2	17.7	0.0	7.0	.979
LLI	1.0	0.2	1.0	0.1	0.0	0.1	.509
PI-LL (°)	-0.7	7.2	-1.3	5.4	-0.6	6.5	.787
SVA (mm)	-11.8	22.3	-12.4	19.1	-0.6	17.0	.913
GT (°)	17.1	6.2	15.8	6.2	-1.3	5.3	.469

use of a domino connector during the compression maneuver allows for additional lordotic correction.

SPO, PSO, and Posterior Vertebral Column Resection

Rigid and angular kyphosis in the proximal thoracic spine presents a particularly challenging pathology regarding the risk of spinal cord injury. Surgical correction options include posterior-based procedures such as the SPO, the PSO, and the pVCR (posterior vertebral column resection). SPOs are limited to the sagittal plane and aimed at deformity patients with adequate disc height and residual flexibility within the intervertebral disc. However, SPOs lose their utility in patients with severe rigid thoracic kyphosis. pVCR is a more effective technique to correct severe kyphotic deformity, but remains a demanding procedure with high risks of complications, including significant blood loss and risk of neurological deficit. Traditionally, the pVCR is

considered appropriate in patients with a poor baseline neurological status.^{9,10}

Historically, the advantage of the PSO in the lumbar spine was that it allowed for adequate operative correction without introducing the additional morbidity associated with an anterior exposure. However, a thoracic PSO differs from lumbar PSO in several ways. A thoracic PSO requires a more rigorous exposure to mobilize the thoracic spine and a posterolateral approach to avoid spinal cord injury. To achieve this, a bilateral costotransversectomy resection must be performed. When the osteotomized vertebra is identified, the rib should be cut at least 5 cm from the costotransverse joint. During this resection, pleural tears are frequent, but thoracic drains are not always necessary as wound closures provide good pleura seals. Another difference in proximal thoracic osteotomies is the importance of external maneuvers during the correction procedure. This maneuver requires the head to follow the upper spine during the correction to avoid spinal injuries. Coordination between the surgeon performing the

TABLE 4. Baseline and 2-yr Postoperative Oswestry Disability Index (ODI) Scores for Each Patient

Patient	Age/gender	Preop ODI	Postop ODI
1	25/F	48	35
2	69/F	30	21
3	76/M	42	38
4	32/M	42	27
5	17/F	12	11
6	15/F	25	15
7	17/M	2	10
8	66/F	56	2
9	32/M	34	42
10	58/M	36	24

FIGURE 8. Twenty-five-year-old female preoperative EOS™ radiography (EOS™ imaging) presenting an iatrogenic proximal junctional kyphosis. We can observe a C2-C7 cervical hyperlordosis to compensate the proximal thoracic kyphosis.

FIGURE 9. Preoperative CT scan with 86° T2-T6 kyphosis. CT scan is mandatory for preoperative planning. There is a posterior fusion extended to T1 and an anterior fusion at the kyphosis apex.

surgery and the surgeon holding the freed Mayfield frame (Integra LifeSciences) is crucial to allow, as gently as possible, movements of the spinal cord.

Limitations

O'Shaughnessy et al⁵ recommended performing multiple smaller PSOs to limit the neurological risk. However, the current series reported a mean correction of 25.7° at the PSO level (Figures 8-10). This correction is higher than the series reported by O'Shaughnessy et al⁵ or Lafage et al,¹¹ with mean correction

of 10.7° for both. Several points can explain differences in correction magnitude, such as performing the PSO at the apex of the kyphosis, removing the upper intervertebral disc, external maneuvers, and the need for a costotransversectomy to easily access the vertebral body. Despite the higher magnitude of correction, no neurological complications were reported in this series. However, a mean blood loss of 1650 mL and 2/10 cases of hemothoraces were reported. This technique warrants a lateral

FIGURE 10. Postoperative EOS™ radiographs (EOS™ imaging) after a single level T5 PSO with 30° segmental correction. The C2-C7 cervical lordosis has decreased and C0-C2 angle has increased to maintain horizontal gaze.

access to the vertebral body to increase the resection capacity, amount of correction, and decrease the risk of neurological retraction. Therefore, careful removal of the rib is needed to stay in the extrapleural space. This is, however, consistent with the high level of morbidity associated with such challenging procedures.^{9,10}

Interpretation

Impact of upper thoracic PSO on cervical alignment: this study reported a reciprocal improvement in the regional cervical sagittal alignment following upper thoracic PSOs. The interplay between cervical and thoracolumbar alignment is established in the literature.¹² Obeid et al reported that patients with thoracolumbar deformity recruit cervical hyperlordosis as a compensatory mechanism to maintain horizontal gaze. They concluded that the correction of LL by a lumbar PSO resection of 37° led to a 6° spontaneous reduction of distal CL.¹³ Moreover, Blondel et al¹⁴ demonstrated that differences in postoperative thoracolumbar alignment lead to different reciprocal changes in cervical spine. Finally, similar cervicothoracic osteotomies at C7 and T1 levels are recently described by Deviren et al as safe and effective procedures for the management of cervical kyphotic deformity. However, the technique described in this study highlights important aspects, not previously reported, such as the resection technique: preserving 5 to 10 mm of anterior

cortex, avoidance of temporary rods, navigation guided resection, Mayfield-assisted correction, and domino connectors. Both Deviren et al and the current study further emphasize the importance of upper thoracic PSOs as a possible management option for both cervical and upper thoracic deformities.¹⁵ Although modifications were observed in the craniocervical system, no significant changes were observed in spinopelvic alignment (SVA, PT, and PI-LL). Postoperative changes, following a proximal thoracic PSO, mainly lead to cervical spine adaptations. It illustrates the close relationship between the proximal thoracic spine and the cervical spine.

CONCLUSION

Proximal thoracic PSO is a safe and effective, albeit technically demanding surgical procedure for the management of patients with focal hyperkyphosis. Beside the excellent correction in thoracic hyperkyphosis, a thoracic PSO provides spontaneous relaxation of the cervical hyperlordosis usually recruited by these patients to maintain horizontal gaze. This study provides a step-by-step approach to performing the proximal thoracic PSO technique with special consideration to the relevant surgical tips that have the potential to improve clinical and radiographic outcomes.

Disclosures

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