Journal of Orthopaedic Translation 23 (2020) 1–7

Contents lists available at ScienceDirect

Journal of Orthopaedic Translation

journal homepage: www.journals.elsevier.com/journal-of-orthopaedic-translation

Original Article

In vivo deformation of the spine canal before and after surgical corrections of severe and rigid kyphoscoliosis

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A R T I C L E I N F O

Keywords:
Kyphoscoliosis
Spinal canal length
3D-model reconstruction
Ponte osteotomy
vertebral column resection

A B S T R A C T

Background: Ponte osteotomy and posterior vertebral column resection (PVCR) are two popular surgical techniques in treatment of severe and rigid kyphoscoliosis. However, quantitative effects of the two surgeries on spinal cord deformation are unclear. This information is critical for improvement of the treatment methods that can maximally correct the spinal deformity and prevent neurological complications.
Methods: Ten patients with severe kyphoscoliosis were investigated. X-ray and CT images of full spine of all patients were acquired before and 6–24 months after surgical treatment using either Ponte osteotomy or PVCR. A 3D model of the spine was constructed for each patient using the CT images that included the spinal canal between T2 and L2 vertebrae. The spinal canal length (SCL) was determined at 5 locations on the cross section of the canal: anterior, posterior, left, right (concave or convex side) and centre positions. The perpendicular distances between the T2 and L2 vertebrae, COBB angles and patient reported outcome measures before and after operations were determined.
Results: For patients treated with Ponte osteotomy, the SCLs were elongated by 12.7 $\pm$ 9.5 mm (5.4 $\pm$ 3.9%) at the concave side and 3.2 $\pm$ 6.8 mm (1.3 $\pm$ 2.8%) at the convex side. The COBB angle was corrected by 55.8% and the T2-L2 distance was increased by 66.1 $\pm$ 12.0 mm (68.4 $\pm$ 15.9%). For patients treated using PVCR, the SCLs were shortened by -5.5 ± 5.3 mm (-2.3 ± 2.2%) at the concave side and -14.0 ± 6.6 mm (-5.2 ± 2.6%) at the convex side. The COBB angle was corrected by 60.0% and the T2-L2 distance was increased by 41.5 $\pm$ 12.4 mm (32.1 $\pm$ 23.0%). The patient reported outcome scores were improved using both surgeries ($p < 0.05$).
Conclusion: Ponte and PVCR surgeries caused significant changes of the SCL in scoliosis patients in different ways. The Ponte osteotomy mainly caused elongation of the SCL at concave side and the PVCR caused compression of the SCL at the convex side. Both surgeries partially improved the spinal deformity. The data provide insights for development of new surgical techniques that integrates the advantages of both Ponte and PVCR osteotomies to maximally correct the spine deformity and prevent neurological complications.
The translational potential of this article: The methodology and the data presented in this paper could be instrumental for development of computer assisted surgical techniques that can maximally correct the spinal deformity and minimize the effect on the spinal cord in scoliosis patients.

Introduction

Severe and rigid kyphoscoliosis negatively affects patients' life quality, and could result in deterioration of patients' cardio-pulmonary function if left without treatments [1,2]. However, surgical treatment of severe kyphoscoliosis has always been a challenge because of the technical difficulties, possible intra- and post-surgical complications, and especially the neurological deficits [3–6]. Contemporary surgical techniques include Ponte osteotomy that is aimed to improve the flexibility of the whole spine for realignment by removing the lamina, facet joint and ligaments between adjacent segments [7], and the posterior vertebral column resection (PVCR) that directly shortens the spine by absolute

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https://doi.org/10.1016/j.jot.2020.03.009
Received 16 January 2020; Received in revised form 11 March 2020; Accepted 15 March 2020
Available online 10 April 2020

removal of the apical vertebral to correct the deformity and release the tethered spinal cord [8]. Ponte osteotomy is easy to operate but difficult to correct severe sagittal imbalance due to limited posterior column shortening; PVCR is helpful in spinal translation but with a high risk of neurological deficit, more blood loss and longer operating time. Although these surgeries can generally result in satisfactory clinical outcomes and partially correct the spinal deformity for kyphoscoliosis patients [9–12], post-operative neurological complications have been often reported [8, 13–15]. Understanding the mechanisms causing neurological complications is critical for improvement of the surgery that could prevent the neurological complications and maximize the spinal deformity corrections.

Excessive distraction or compression of the spinal cord during the corrective surgeries has been assumed a factor that could trigger the neurological deficits and cause damages to the spinal cord [1,16,17]. Animal models have been used to quantify the maximum distraction lengths that could cause spinal cord injuries [18,19]. Scoliosis patients have been investigated to determine the post-operative changes of the spinal cord lengths that were associated with no neurological complications [20,21]. These studies measured the spinal cord or canal using two-dimensional plane curves outlined on the X-ray or CT images. However, in severe kyphoscoliosis patients, the spinal cord is deformed in space. A plane curve model could not accurately or correctly represent the complicated geometry of the spinal cord. No data has been reported on the changes of the 3D anatomical spinal cord lengths of scoliosis patients after corrective surgeries. There are no reference data on spinal cord elongations that could be used to optimize corrective surgeries that could maximize the corrections of the deformed spine without causing neurological complications.

The objective of this study was to investigate the 3D changes of the spinal canal lengths (SCLs) of severe kyphoscoliosis patients with satisfactory clinical outcomes after surgery using either Ponte osteotomy or PVCR. Three-dimensional models of the spine including the spinal canal were constructed for each patient using his/her 3D CT images captured preoperatively and postoperatively using an established technique in our previous study [22]. In this study, using the 3D canal model, we measured the postoperative changes of the SCLs at five different locations around the cross-section of the canal. We hypothesize that the spinal canal experiences different deformations at different locations after the corrective surgery.

Materials and methods

Ten patients (6 females and 4 males, 21 ± 3.77 years old) who suffered severe and rigid kyphoscoliosis and surgically treated between 2016 and 2018 were retrospectively investigated in this study (Table 1). All patients suffered thoracic or thoracolumbar cure (coronal and sagittal Cobb angles >100°). Seven patients were diagnosed with early onset scoliosis and 3 patients with adolescent idiopathic scoliosis. No patient had previous history of surgical treatments. All patients were treated with traction before surgery. Preoperative bending X-rays of full spine showed that the flexibility indexes of all patients were under 25% and confirmed rigid kyphoscoliosis. All patients were treated by the same surgical team using posterior pedicle instrumentation with 5 treated by Ponte osteotomy and 5 by PVCR. Patient were asked to complete the outcome measures (including SRS-22, SF-36, JOA and VAS questionnaires) at 3, 6, 12, 24, 36 months, postoperatively. The patient reported outcomes (PROs) at the last available follow-up of all patients were analysed in this study.

Table 1
Characteristics of the patients.

Characteristics	Ponte	PVCR	P value
	Mean ± SD	Mean ± SD	
Age (ys)	22.4 ± 2.7	20.4 ± 5.5	0.484
Height (cm)	133.8 ± 6.5	142.6 ± 6.1	0.058
Weight (kg)	37.8 ± 4.4	41.4 ± 4.7	0.247
BMI	19.5 ± 3.9	20.5 ± 2.9	0.679
Follow-up (m)	12.0 ± 4.2	14.4 ± 9.1	0.802
Preoperative radiographic parameters			
Cobb angle (°)	159.5 ± 9.4	139.0 ± 24.4	0.114
Kyphosis (°)	152.8 ± 10.0	146.1 ± 33.2	0.691
T2-L2 distance (mm)	97.8 ± 10.9	165.7 ± 64.3	0.048
AVT (mm)	65.1 ± 8.2	70.3 ± 30.3	0.720

AVT, apical vertebral translation; PVCR, posterior vertebral column resection.

Surgical technique

Under general anaesthesia, each patient was positioned in prone with a posterior middle incision. Subperiosteal exposure of posterior elements of the spine was performed. If the intervertebral mobility was acceptable, the Ponte osteotomy was performed. Pedicle screws were inserted in both sides, and precurved titanium rods were inserted. After the rod insertion, the scoliosis was preliminary realigned using rod-derotation techniques. Direct segmental derotation technique was then used to enhance the vertebral derotation outcome around the apical vertebra. Because the deformity was rigid, an asymmetrical Ponte osteotomy averaged by four levels was performed on five patients. A sequential segmental compression and cantilever manoeuvre were used to close the osteotomies and correct the kyphosis. Correction outcome was then enhanced by conventional correction techniques including distraction, compression, and translation. After correction, bone graft was placed. The wound was closed after irrigation and drains.

If the intervertebral mobility was poor or there was fused vertebral body with flexibility less than 10%, then the PVCR was performed by one level of the deformity. Pedicle screws were inserted on both sides of the vertebrae except for apical vertebra. A temporary rod contoured to the shape of the deformity was first inserted to keep the spine in a stable position when the resection procedure was in process. After a wide laminectomy and bilateral decompression of the spinal cord and nerve roots, resection of the vertebral column was performed from the lateral side but not across the midline. The temporary rod was removed when the resection was carried out unilaterally. The previous procedure was repeated on the opposite. After the entire vertebral body and adjacent discs were totally removed, the titanium mesh containing cancellous bone was inserted between the two adjacent segments. After placement of the mesh, the wound was closed after irrigation and drains. SSEPs were used to monitor the neurological response of the spinal cord during the entire operation.

Radiographic analysis

For each patient, full spine X-ray and CT images (Siemens, Germany) were acquired within 1 month before and after the operation (with a 1 mm thickness and a resolution of 512 × 512 pixels). All CT images were taken in the supine position. Coronal and sagittal plane angles, and apical vertebrae translation were defined on the full spine X-ray image (Fig. 1). Preoperative and postoperative Cobb angles were measured between the upper and lower end vertebrae (U/L-EV) which are defined as the most tilted vertebrae from the coronal plane (Fig. 1). The correction rate of Cobb angles is defined as the difference between the postoperative and preoperative angles divided by preoperative angle. The change rates of other variables were defined similarly.

Three-dimensional model analysis

The 3D CT images of each patient were input into the 3D-slicer software (V.4.10.1, open access, BWH and 3D Slicer contributors) to reconstruct a 3D surface model of the spine because 3D reconstruction of the spine using CT images has been recognized as the gold standard for analysis spinal geometry. The model was then input into the Rhinoceros

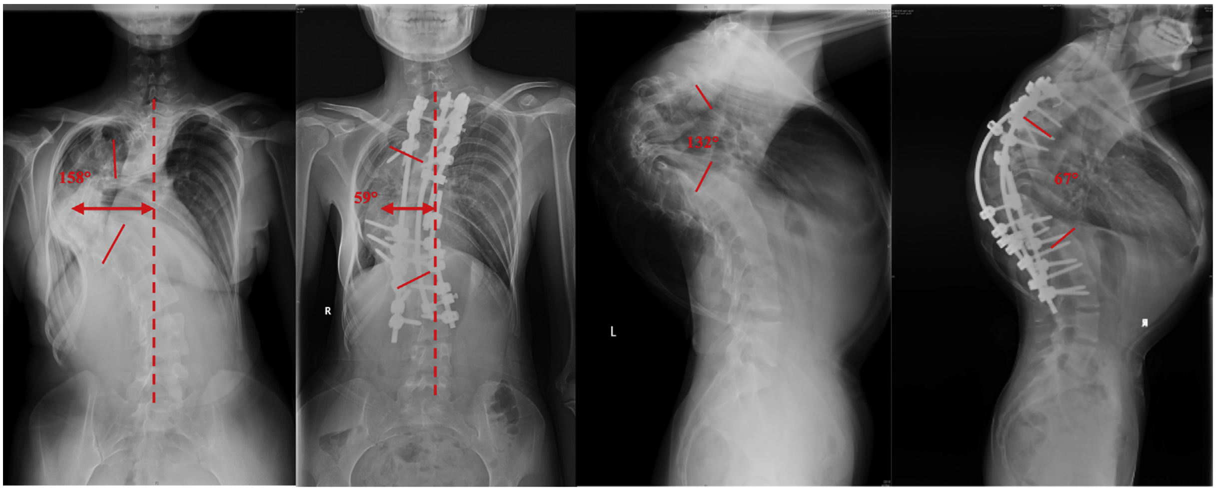

Figure 1. Full spine X-ray of a patient with kyphoscoliosis who underwent posterior pedicle instrumentations and corrected by Ponte osteotomy. The Cobb angle was measured between a line drawn parallel to the superior endplate of one vertebra and a line parallel to the inferior endplate of the vertebra. The preoperative Cobb angles are 158° and 132° in coronal and sagittal planes, respectively and the postoperative Cobb angles were 59° and 67°, respectively. The coronal and sagittal balance was achieved, and the AVT and the trunk height were improved. AVT, apical vertebrae translation.

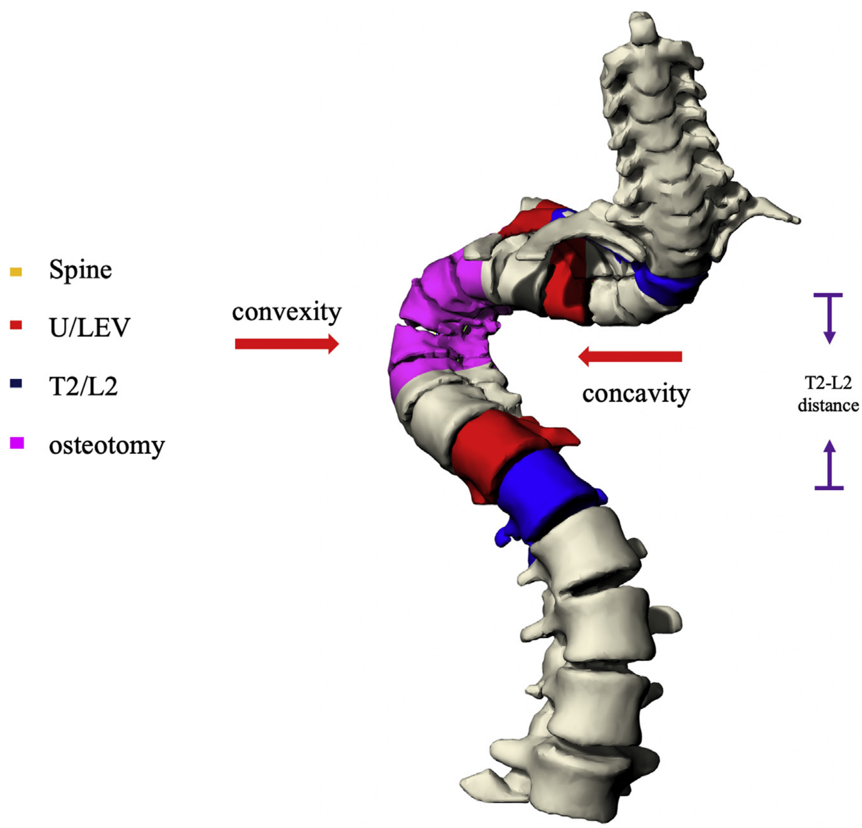

Figure 2. A 3D model of one patient spine was reconstructed using 3D CT images. The T2 and L2 vertebrae were coloured in dark blue, the upper and lower end vertebrae (U/L-EV) in red, the osteotomy segment in pink, and the rest spinal vertebrae in yellow. The distance between T2 and L2 was measured from the vertebral centres of the two vertebrae. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

software (V. 5.5.2, Robert McNeel Associates, WA) for measurements of the geometric parameters of the spine after mesh-reduce process. Different vertebrae were marked using different colours to ease the data analysis (Fig. 2).

As the spinal cord generally reaches to the L2 level, and the upper instrumented vertebra is normally not higher than the T2 level, the spinal canal was analysed between the L2 and T2 vertebrae in this study. Each selected vertebra was cut in a plane which is parallel to the upper endplate and passing through the centre points of both pedicles in the axial direction of the vertebra (Fig. 3a) to create a cross-section of the spinal canal (Fig. 3b). The canal cross-section was outlined using a closed curve. The area centroid of the cross-section was defined as the central point of the axial spinal canal. Using the anatomic landmarks on the canal, the anterior, posterior, left and right points of the canal were specified. The same location points were connected along the spinal canal by smooth line to represent the length of the spinal canal at different

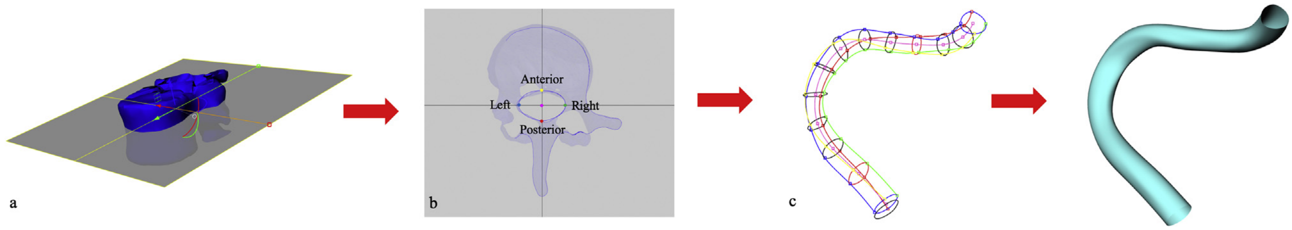

Figure 3. a) The selected vertebra was cut in a special plane and then outlining the cross-section of the spinal canal. Five points were specified: anterior, posterior, left, right, and center points. The concave and convex sides were determined by the SCL lengths of the left and right sides of the canal. Connecting the points in the same location, an intact spinal canal was reconstructed. Using the "length calculation" of Rhino software to measure the SCL in each side. SCL, spinal canal lengths.

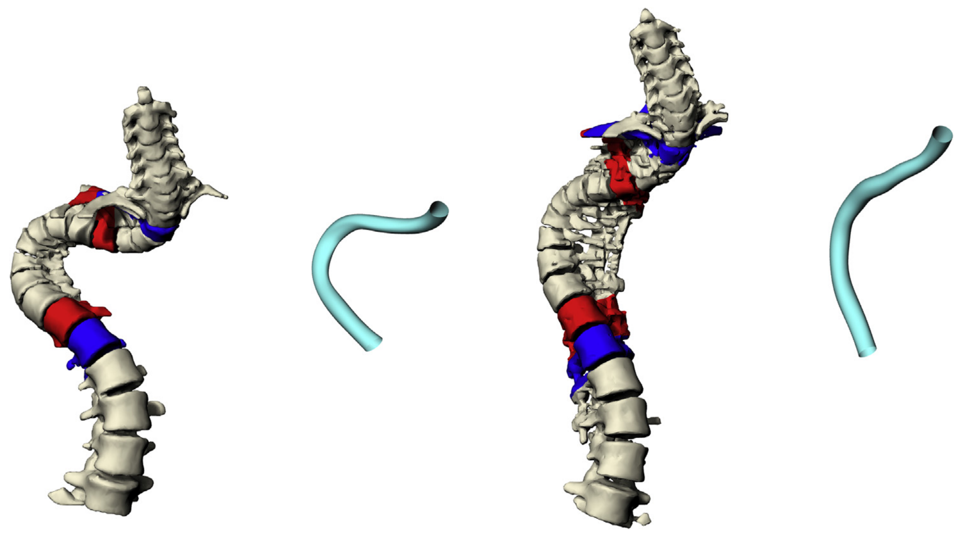

Figure 4. A well-finished reconstruction of the spine and spinal canal preoperatively and postoperatively. The length of spinal canal was calculated by Rhinoceros software.

locations (Fig. 3c). The side having the shortest SCL was defined as the concave side, and the opposite side was defined as the convex side. The length of the spinal canal at each side was measured using the Rhinoceros software (Fig. 3c).

We measured the changes of the SCLs from T2 to L2 before and after the corrective surgery using the Rhinoceros software (Fig. 4). Specifically, the length changes at the 5 selected locations were measured. As a measure of the effectiveness of the corrective surgery, we also measured the perpendicular distances between the central points of T2 and L2 vertebrae (Fig. 2). All the measurements were calculated by Rhinoceros software. The accuracy of using the 3D CT model to simulate human musculoskeletal system was validated previously [23].

Statistical analysis

SPSS 22.0 was used for statistical analysis. All results were expressed in terms of mean and standard deviation (mean ± SD). A one-way measure analysis of variance (ANOVA) was performed to analyse the SCL changes and correction rates. The data between the Ponte and PVCR patient groups, including radiographic parameters, the changes and correction rates of the SCLs were tested using an independent-sample t test. A significant difference was defined when $p < 0.05$.

Results

There was no significant difference in patient's conditions, including radiographic parameters, between the Ponte osteotomy and PVCR groups except for T2-L2 distance ($p = 0.048$) and the body heights ($p = 0.058$) between two groups (Table 1). The Ponte osteotomy improved the COBB angles by 89 ± 17° (56 ± 11%) ($P < 0.05$) and the perpendicular distance between the T2 and L2 vertebrae by 66.1 ± 12.0 mm (68.4 ± 15.9%) ($P < 0.05$). The PVCR improved the COBB angles by 84 ± 19° (60 ± 10%) ($P < 0.05$) and the T2-L2 distance by 41.5 ± 12.4 mm (32.1 ± 23.0%) ($p < 0.05$). No significant differences in postoperative Cobb angles ($p = 0.209$ in coronal and 0.655 in sagittal planes) were observed between the two patient groups, but there was a significant difference between the T2-L2 distance improvements of the Ponte osteotomy and PVCR ($p < 0.05$) (Table 2). Both Ponte osteotomy and PVCR improved the PRO scores significantly (Table 3) ($P < 0.05$) at the last clinical follow-up (in average at 13.8 months after operation, range: 6–24 months).

The changes of the SCLs were shown in Table 4. For Ponte osteotomy, the SCL was significantly elongated by 12.7 ± 9.5 mm (5.35 ± 3.89%) at the concave side ($p < 0.05$) and by 3.2 ± 6.8 mm (1.32 ± 2.79%)

Table 2
Postoperative radiographic parameters and outcomes of the patients.

Radiographic parameters	Ponte	VCR	P value
	Mean ± SD	Mean ± SD	
Postoperative Cobb angle (°)	70.7 ± 18.3	55.5 ± 16.6	0.209
Delta change (°)	88.8 ± 17.4	83.5 ± 18.9	0.655
Correction rate (%)	55.8 ± 10.6	60.0 ± 10.0	0.539
Postoperative kyphosis (°)	69.12 ± 10.94	64.1 ± 22.2	0.660
Delta change (°)	83.7 ± 16.5	82.1 ± 22.6	0.660
Correction rate (%)	54.5 ± 8.1	56.4 ± 10.4	0.764
Postoperative T2-L2 distance (mm)	162.9 ± 14.0	207.1 ± 52.5	0.106
Delta change (mm)	66.1 ± 12.0	41.5 ± 12.4	0.012
Correction rate (%)	68.4 ± 15.9	32.11 ± 23.0	0.020
Postoperative AVT (mm)	35.8 ± 7.0	37.3 ± 20.4	0.878
Delta change (mm)	−29.4 ± 10.6	−33.1 ± 14.1	0.654
Correction rate (%)	−44.5 ± 12.2	−50.8 ± 16.0	0.500

AVT, apical vertebral translation.

Table 3
Patients report outcomes scores.

PROs	Ponte			VCR		
	Preoperative	Postoperative	P value	Preoperative	Postoperative	P value
SRS-22	83.2 ± 4.8	93.6 ± 5.8	0.004	81.8 ± 7.7	91.6 ± 7.5	0.022
SF-36	85.0 ± 3.5	94.8 ± 1.3	0.004	85.6 ± 3.4	93.6 ± 1.9	0.016
mJOA	25.4 ± 1.1	26.8 ± 0.8	0.005	26.2 ± 1.1	27.4 ± 0.5	0.033
VAS	2.4 ± 1.5	1.2 ± 0.8	0.033	3.0 ± 0.7	1.0 ± 1.0	0.003

PROs: patient reported outcomes, SRS-22, Scoliosis Research Society Outcomes, SF-36, Short Form Healthy Survey, mJOA: Japanese Orthopaedic Association scores, VAS: Visual Analogue Scale

Table 4
Changes and correction rates of the SCL.

Locations	Ponte				VCR			
	Pre-op (mm)	Post-op (mm)	Delta (mm)	Correction Rate(%)	Pre-op(mm)	Post-op(mm)	Delta(mm)	Correction Rate(%)
Concave	236.12 ± 19.75	248.82 ± 23.35	12.70 ± 9.47[a]	5.4 ± 3.9	247.549 ± 12.143	242.00 ± 13.47	−5.55 ± 5.30	−2.3 ± 2.2
Center	243.04 ± 15.28	251.04 ± 17.37	8.00 ± 8.08	3.3 ± 3.4	259.223 ± 14.318	249.52 ± 16.99	−9.71 ± 5.81[a]	−3.8 ± 2.3
Convex	257.48 ± 17.19	260.63 ± 13.81	3.15 ± 6.82	1.3 ± 2.8	273.456 ± 17.965	259.45 ± 22.13	−14.01 ± 6.6[a]	−5.2 ± 2.6
Anterior	251.51 ± 20.07	261.81 ± 15.99	10.30 ± 6.15[a]	4.2 ± 2.7	271.36 ± 18.90	260.69 ± 19.14	−10.66 ± 4.96[a]	−3.9 ± 1.9
Posterior	240.47 ± 17.31	251.62 ± 266.10	11.16 ± 9.56	4.8 ± 4.2	267.58 ± 12.02	253.45 ± 15.63	−14.13 ± 5.96[a]	−5.3 ± 2.4

[a] Significant difference of SCL after surgery ($p < 0.05$). SCL, spinal canal lengths.

($p > 0.05$) at the convex side between the T2 and L2 vertebrae after the corrective surgery. For the PVCR surgery, the SCL was shortened by −14.0 ± 6.6 mm (−5.20 ± 2.62%) between the T2 and L2 vertebrae ($p < 0.01$) at the convex side and by −5.6 ± 5.3 mm (−2.25 ± 2.15%) ($p > 0.05$) at the concave side.

Discussion

This study investigated changes of SCLs of patients with severe scoliosis after treatment using either Ponte osteotomy or PVCR surgeries. The data indicated that both surgeries helped improve clinical outcome scores, partially corrected the spine deformity (COBB angles) and increased the spinal height along the T2-L2 segment. Both surgeries caused changes of the SCL but in different ways. The Ponte osteotomy mostly elongated the spinal cord at the concave side of the deformed spine with less effect on the convex side. The PVCR surgery mostly shortened the spinal cord at the convex side with less effect on the concave side. The data proved our hypothesis that the spinal canal experiences different deformations at different locations after the corrective surgeries.

Few studies have reported on the changes of the SCLs in the centre of the canal in scoliosis patients after surgical treatments [20,21,24,25]. Bridwell et al. [20] measured the preoperative and postoperative full spine X-ray images of patients with scoliosis and showed an average of 13.47 mm lengthening of the centre of the spinal canal between the upper and lower end vertebrae. Yahara et al. [21] reported that for patients after a posterior correction, the central SCLs were elongated by an average of 10.1 mm between the T2 and L2 vertebrae. Our data showed on average an 8.0 mm elongation in the spinal canal centre between the T2 and L2 vertebrae for patients operated using the Ponte osteotomy method, that are lower than the data reported in literature. Owing to different measurement techniques and patient conditions, however, it is hard to make a direct comparison between these studies. X-ray is widely used in clinical evaluation of spinal outlines of patients. However, it is hard to identify the spinal canal on 2D images due to the overlapping of complicated spinal elements, such as the vertebral column, lamina, and the spinous process, particularly on the severe scoliotic spine, which leads to the inaccurate results. Compared with 2D images, 3D spinal reconstruction was shown to be more accurate in evaluation of spinal geometry [26]. The intrinsic shape of the spinal canal could be observed from the reconstructed model to facilitate a precise measurement. Our measurements were based on preoperative and postoperative 3D in vivo spinal canal models that could provide an accurate measurement of the spinal canal deformation compared with those reported in literature.

Spinal cord injury during operation is detrimental, but the injury mechanism is difficult to determine. Cusick et al. [17] conducted an investigation using primate animals and reported that intraoperative distractions could cause acute mechanical injuries in spinal cord components (fibre tracts). To quantify the spinal cord damage, Qiu et al. [18] reported that a SCL distraction over 11.8 mm could cause spinal cord damage in a goat model; Yang et al. [19] reported that a parallel distraction distance of 20.2 mm (3.6%) could lead to spinal cord injury in a porcine model; and Yahara et al. [21] confirmed that a distraction of the centre of human spinal cord within 10.1 mm (3.6%) is safe for spine deformity correction. The patients in our Ponte surgical group experienced a 3.3% elongation at the concave side measured between the T2 and L2 vertebrae. However, because the elongation rate calculation depends on the segment length and location in the spinal canal and owing to the anatomic differences of different species, it is impossible to evaluate the patient conditions using the data measured from animal models. Further, all previous studies reported the changes of centre line of the spinal canal, but the intraoperative monitoring of the spinal cord always showed neural potentials to change in one side of the body [27] and pathological damage on the cord is uneven [28]. Therefore, it may be insufficient to use the changes of the central length of the SCL to evaluate the neurological deficits during the surgery. The changes of the SCL in the concave and convex sides as demonstrated in our study could be more appropriate for improvement of surgical techniques to accurately monitor the neurological deficits during operation.

Compared with the SCL elongation, less attention has been devoted to the effect of spinal cord compression during operation. Although the PVCR has been verified as a safe and effective approach to release spinal cord pressure and correct severe deformities, over-shortening or compression of the spinal cord during surgery could lead to twisting/compressing of the spinal cord that could also result in neurological deficit [1,2,4,8,29]. However, except Li et al. [25] who reported that the central spinal canal was shortened by 17.0 mm in average after the PVCR surgery, no data have been reported on the spinal cord compression using accurate 3D-models of the spine. In our study, the spinal canals of all patients were corrected by one level PVCR. We showed that the surgery could shorten the SCL on average by 14.0 mm, 9.7 mm, and 5.5 mm at the convex side, center, and concave side, respectively, indicating the

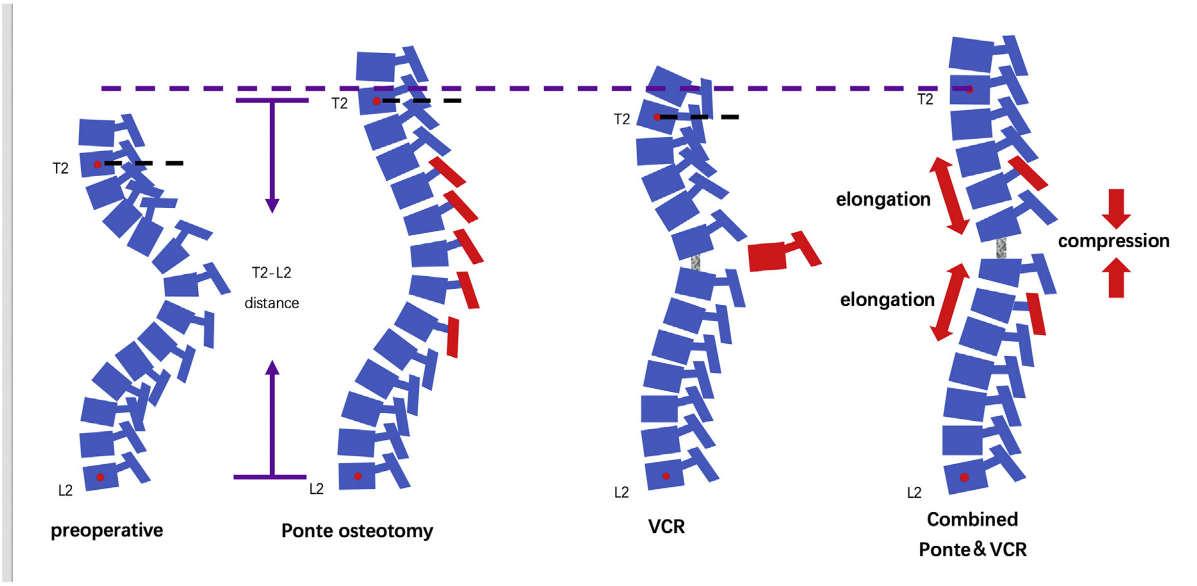

Figure 5. Schematic diagrams of a scoliosis spine before correction, after Ponte osteotomy, after PVCR, and after a hybrid osteotomy. PVCR, posterior vertebral column resection.

different deformation levels when measured at different locations of the canal.

Satisfied correction and outcomes have achieved by using Ponte osteotomy and PVCR [30–32]. Ponte osteotomy significantly increases the flexibility of the spine by removing the posterior elements from the pedicle to pedicle and shortening the posterior column to correct the deformity on two planes [7]. For severe kyphoscoliosis, spinal translation is crucial for correction, and PVCR is the only technique that could provide this correction and release the tensive spinal cord [2]. However, this is a highly difficult technique and should be performed by experienced surgeons. Possible instability could occur due to the resection that breaks the continuity of the spine but that cannot be strongly hold using a titanium cage. Compared with PVCR that usually takes longer operating time, with more blood loss and a higher risk of spinal cord injury due to the violent segmental resection, Ponte osteotomy is a relatively safe and easy operation that could provide an immediate and long-term stability. Ponte osteotomy is suitable for the spinal column that has intervertebral mobility identified by bending X-ray images and intraoperative observations. PVCR is more suitable for the palpable fused vertebral body, especially for correcting sharply angular kyphosis on sagittal plane. An accurate preoperative plan should be based on the surgeon's experience and the patient's actual situation.

In this study, all the patients were without neurological complications during postoperative follow-up studies. Both surgical techniques produced significant clinical improvements measured using PRO scores ($P < 0.05$) and partially corrected the spinal deformity. However, it is interested to note that both surgical techniques resulted in different deformation patterns to the spinal canal. The Ponte osteotomy was more focused on the releasing of the tightness at the spinal curve of the scoliosis [7]. Therefore, it could increase the distance between T2 and L2 vertebrae by enlarging the intervertebral space and elongating the spinal canal at the concave side [7]. The PVCR was more focused on the releasing of the tightness through a resection at the convex side of the rigid scoliosis [1]. Therefore, it could correct the spinal deformity and increase the distance between T2 and L2 vertebrae by reducing the convexity at the apex area [1]. The data reported in literature [18,19,25] and in this study indicated that the spinal cord could withstand both distraction and compression. Because these patients were without intraoperative and postoperative neurological complications, the amount of spinal cord distractions and compressions measured among these patients could be used as the safe range for evaluation of spinal cord deformation during corrective surgeries.

The distinct effects of the two surgical techniques on the 3D deformation of the spinal cord could provide baseline data for improvement of surgical techniques that are aimed to maximize the spine deformity correction. Both surgical techniques were shown to correct the spinal deformity by about 60%. A hybrid surgical technique that combines the advantages of the two surgical techniques could further correct the spinal deformity without causing additional changes of the deformation of the spinal cord, as illustrated in Fig. 5. This hybrid surgery adopts the function of Ponte osteotomy that causes elongation of the spinal cord and the PVCR that causes compression of the spinal cord. Therefore, a combination of the two techniques could result in an increase in correction of the spinal deformity without causing extra changes to the spinal cord deformation and thus helping prevent neurological complications. Future studies are warranted to explore the feasibility and surgical efficiency of the hybrid corrective surgery in maximally correcting the spinal deformity and at the same time minimizing the deformation of the spinal cord to prevent neurological complications.

There are several limitations in this research. The patients' number is small owing to the availability of patients that can be used to compare the two corrective surgeries. Larger number of patients should be investigated in future to help define and validate the safe region of spinal cord deformation. No patients treated with other surgical techniques, such as pedicle subtraction osteotomy and posterior column osteotomy, were available in our institution. All the patients underwent the CT scan in supine position, which cannot represent the spinal canal morphology under weightbearing conditions. Owing to retrospective nature of the study, all patients were without neurological deficits and reported with fair clinical outcomes. Despite these limitations, this study did provide the 3D deformation data of the spinal canal of patients with severe kyphoscoliosis that were not associated with neurological complications after treatments using the two popular corrective surgeries.

Conclusion

In conclusion, our data demonstrated that the Ponte osteotomy elongated the SCL in concave side and produced moderately changes in the convex side, whereas the PVCR surgery shortened the spinal canal more in the convex side than in the concave side. Both corrective surgeries contribute to the partial corrections of the spinal deformity and increases of the T2-L2 distances. However, the two surgeries achieved correction goals by causing different deformations in the spinal canal. The data could provide insight for determination of safe ranges of spinal cord deformation and for development of new hybrid surgical techniques that maximize the correction of spine deformity and minimize the deformation of the spinal cord in severe and rigid kyphoscoliosis patients.

Ethical approval

This is a retrospective analysis of our previous clinical data. Our hospital IRB approved this study without requiring patient consent. We have the statement on IRB approval in the text.

Conflicts of interest statement

There is no conflict of interest.

Acknowledgements

This research was supported by National Key R&D Program of China (grant: 2019YFC0120604). The authors gratefully acknowledge financial support from China Scholarship Council.

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