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ORIGINAL ARTICLE

Sequential correction technique to avoid postoperative global coronal decompensation in rigid adult spinal deformity: a technical note and preliminary results

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Abstract

Purpose This study aims to evaluate this new sequential correction technique for preventing postoperative coronal imbalance.

Methods Adult Spinal deformity (ASD) patients were stratifies into two types: primary thoracolumbar/lumbar (TL/L) curve with compensatory lumbosacral (LS) curve (Type I) and primary LS curve with compensatory TL/L curve (Type II): for Type I patients: correction of major TL/L curve and one- or two-level segmental rod installed at the convexity of the TL/L curve, L4-S1 TLIF to correct fractional curve and a short rod installed on the contralateral side and installation of long rods; for Type II patients: horizontalize L4 and L5, short rod installation at the convexity of the LS curve, distraction of curve with regional rod and installation of long rods. ASD patients were enrolled with inclusion criteria: with pre-op TL/L Cobb angle more than 30°, with pelvic fixation and with UIV over T10. Radiographic parameters were analyzed.

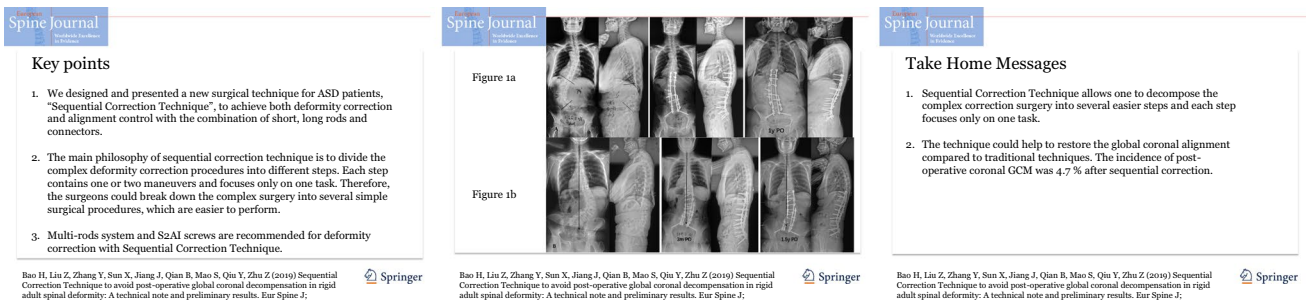
Results Twenty-one patients were recruited (14 patients Type I and 7 Type II patients). Both Cobb angle and coronal offset were significantly improved after surgery. In Type I patients, Cobb angle was improved from 50.48° to 26.91° and coronal offset from 2.94 to 0.95 cm; in Type II patients, Cobb angle was improved from 61.42° to 28.48° and coronal offset from 2.82 to 1.38 cm. In the 10 patients with baseline coronal imbalance, 9 were corrected to coronal balance after surgery.

Conclusion The sequential correction technique allows decomposing the complex correction surgery into several steps, and each step focuses only on one task. It can also reduce the difficulty of rod installation due to the separated maneuvers and multi-rod system.

Level of evidence IV

Graphic abstract

These slides can be retrieved under Electronic Supplementary Material.



Keywords Sequential correction technique · Adult spinal deformity · Coronal imbalance · Global coronal malalignment

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Extended author information available on the last page of the article

Introduction

Adult spinal deformity (ASD) is an increasingly appreciated debilitating pathology with growing incidence of up to 32% in adults and 60% in the elderly [1]. A comprehensive understanding of ASD is necessary so that treatment, both conservative and surgical treatments, could precisely target the underlying etiology. Sagittal malalignment, a key presentation of ASD, has been extensively correlated with decreased health-related quality of life and also serves as the key modifiers in the SRS-Schwab ASD classification [2, 3]. However, global coronal malalignment (GCM) was neglected in ASD patients [4]. Of note, this parameter was initially integrated as a modifier of the Schwab classification of ASD in 2006 but was removed in 2012. However, coronal malalignment in ASD is not a rare condition, the incidence of which is high in primary patients. Ploumis et al. [5] in a small sample size (54 patients) found that 19.3% of degenerative scoliosis patients presented with coronal imbalance (GCM > 4 cm). Moal reported a prevalence of 25% (GCM > 4 cm) in ASD patients [6]. Bao et al. [7] highlighted that 34.8% out of 284 primary degenerative scolioses exhibited a coronal malalignment greater than 3 cm. Moreover, preoperative global coronal malalignment has been associated with an increase in implant failures requiring subsequent removal [8].

The biplanar global malalignment in ASD patients is difficult to correct, especially in those ASD patients with rigid curves. Vertebral osteotomy is commonly performed to correct the rigid curves and the fusion down to pelvis is often required to maintain the postoperative global alignment. However, even with the pelvic fixation, the incidence of iatrogenic coronal malalignment after surgery was reported as high as 30% [7]. Moal et al. [6] also reported that GCM was one of the most likely deteriorated radiographic parameters in ASD patients. In his study, 18% of well-aligned patients at baseline presented a GCM > 4 cm after surgery, similar to the incidence of baseline GCM (25%). Traditionally, spine surgeons use two long rods in surgery to achieve the goals of both deformity correction and global alignment maintenance in rigid ASD patients. Even after osteotomy, the rod installation is still a challenge, and the translation of rods during installation may potentially affect the biomechanical stability of the rods. The goal of controlling both coronal and sagittal global alignments is also difficult to achieve with only two long rods, which would lead to global malalignment and even implant failure.

Based on our experience, we designed and presented a new surgical technique for ASD patients, "sequential correction technique," to achieve both deformity correction and alignment control with the combination of short rods, long rods and connectors.

Materials and methods

Indication and baseline evaluation

The sequential correction technique is indicated for adult thoracolumbar/lumbar (TL/L) deformity patients of various etiologies: idiopathic, de novo, congenital, neurofibromatosis Type I, etc. Based on the primary driver of deformity, the patients can be stratified into two types: primary TL/L curve with compensatory lumbosacral (LS) curve (Type I) and primary LS curve with compensatory TL/L curve (Type II). Typical Type I patients included adult idiopathic scoliosis, adult de novo scoliosis, adult scoliosis with congenital thoracolumbar deformity, etc.; meanwhile, typical Type II patients included adult scoliosis with congenital lumbosacral hemivertebra (Fig. 1). The sequential correction technique is a combination of different surgical procedures, with different orders of procedures for Type I and Type II patients.

The sequential correction technique

Sequential correction of Type I ASD patients

After inducing general anesthesia and performing single-lumen endotracheal intubation, somatosensory evoked potential (SEP) and transcranial motor evoked potential (MEP) monitoring of the spinal cord are initiated. The patient is positioned prone and is prepared and draped as for usual posterior instrumentation and fusion for TL/L scoliosis. The spine is exposed subperiosteally until the transverse processes are reached through a midline posterior incision over the appropriate fusion levels. Then, surgical procedures are performed in the following sequence under continuous neuromonitoring (Fig. 2):

1. All anchors (pedicle screws and S2 alar iliac (S2AI) screws) are placed except on the presumed osteotomy level (the apex of TL/L curve).
2. [Correction]: Asymmetrical three-column osteotomy (3CO) is performed to correct the TL/L scoliosis and/or kyphosis [9, 10], followed by closing the osteotomy site with one- or two-level segmental instrumentation on the convexity of the TL/L curve. The asymmetrical 3CO could be replaced by other correction techniques in this step. Posterior column osteotomies (PCOs) can also be performed in case of non-rigid scoliosis.
3. [Leveling]: L5-S1 transforaminal interbody fusion (TLIF) is then performed from the convexity of the LS curve; L4-L5 TLIF can also be performed if necessary. A short rod is installed on the convexity of the LS curve followed by compression maneuver to horizontalize the

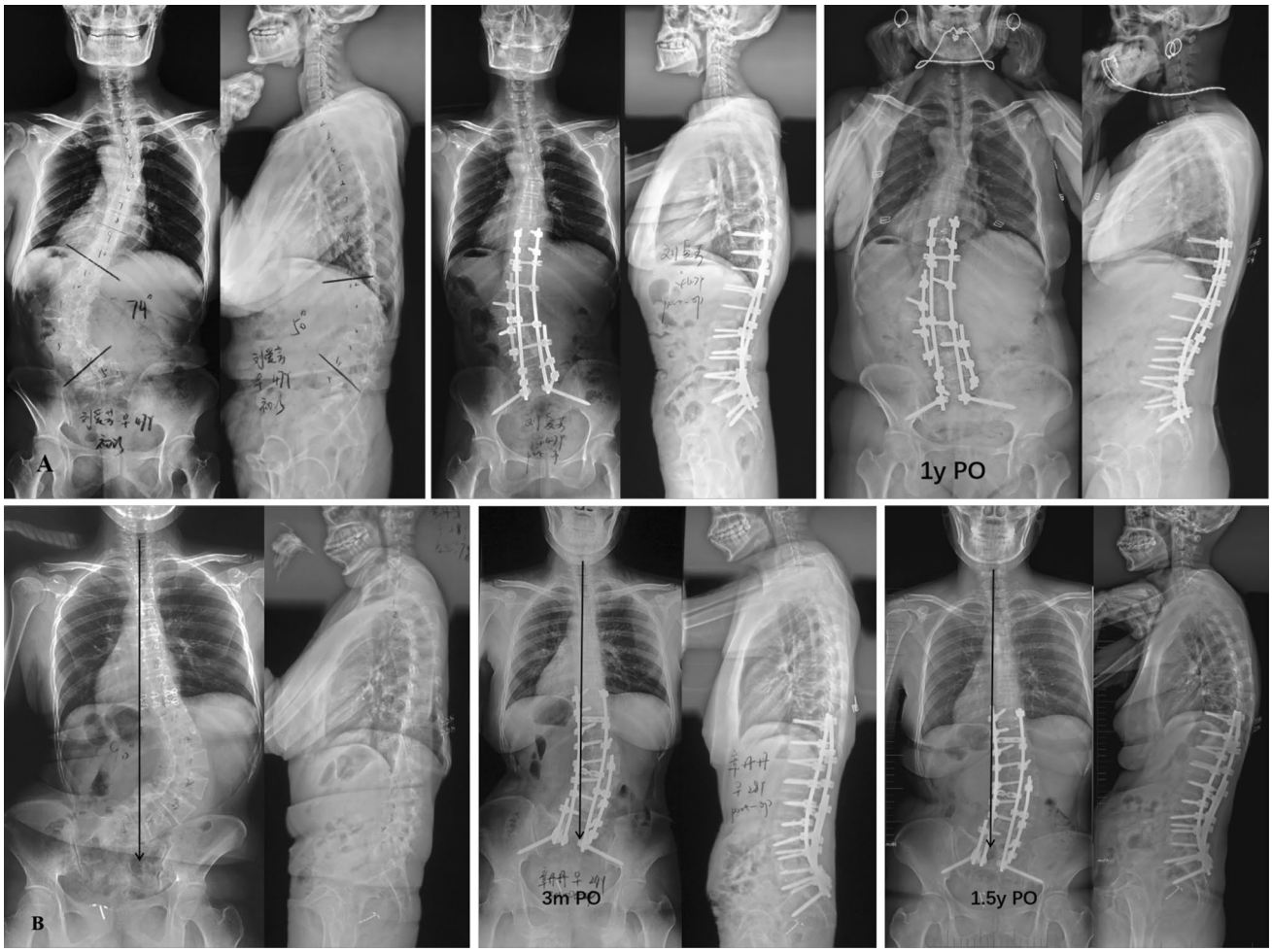

Fig. 1 **a** Type I ASD (primary thoracolumbar curve with compensatory lumbosacral curve), a 47-year-old female with adult idiopathic lumbar scoliosis, the primary curve is lumbar curve; **b** Type II ASD (primary lumbosacral curve with compensatory thoracolumbar curve), a 28-year-old female with congenital L5 hemivertebra; the driver of the deformity is the lumbosacral deformity

L4 and L5 endplate and to pull the L4 and L5 vertebra to the middle line as much as possible.

4. [Integration]: The remaining steps for posterior instrumentation and fusion are then performed. Long rods are inserted from the UIV to pelvis to correct remaining coronal and sagittal imbalance and to achieve solid spino-pelvic fixation. Local bone graft is also placed for sound fusion. The long rods are integrated with short rods using cross-links, Dominos or connectors with two tulips.

Sequential correction of Type II ASD patients

Patients were prepared as above. Surgical procedures are performed in the following sequence (Fig. 3):

1. All anchors (pedicle screws and S2 alar iliac (S2AI) screws) are placed.
2. [LS compression at convexity]: Resection of lumbosacral hemivertebra (or the abnormal bony structure) was performed, followed by anterior support with cage and segmental instrumentation on the convexity of the LS curve. When installing the segmental rod, compression maneuver is recommended to close the osteotomy site and to horizontalize L5.
3. [Distraction of LS curve at concavity]: For the rigid deformity, posterior release at the TL/L curve is recommended with posterior column osteotomies (PCOs). Then, a regional instrumentation from L2 or L3 to S1 is installed at the contralateral side of LS deformity. Distraction maneuver of the LS curve is the key to further realign both the TL/L and LS curves; it could also push the lumbar segments to the middle line to avoid postoperative GCM.
4. [Integration]: The remaining steps for posterior instrumentation and fusion are then performed. Long rods

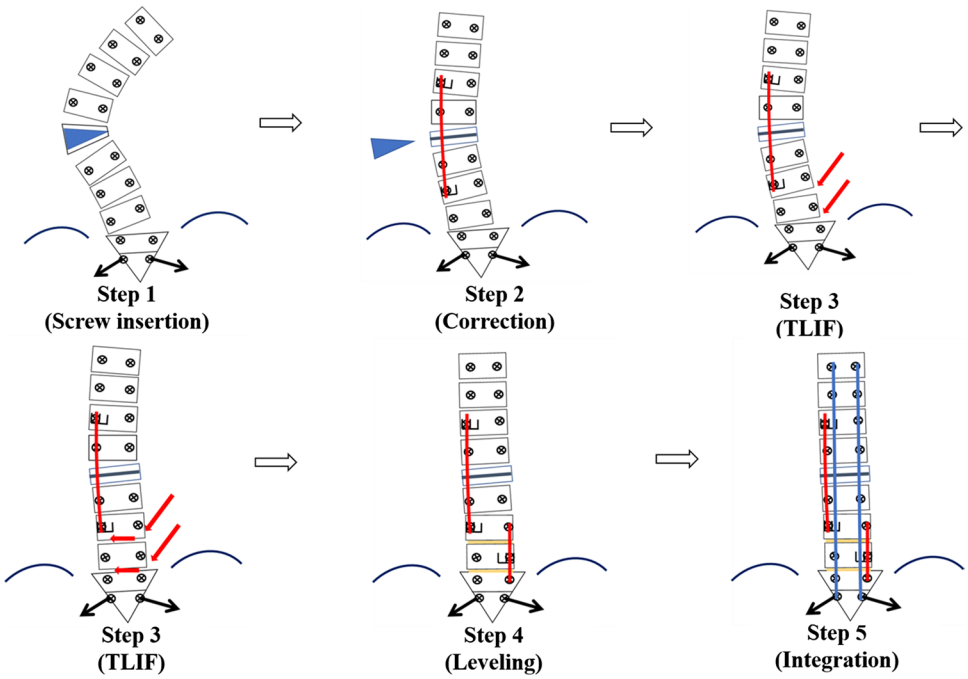

Fig. 2 Schematic diagram of sequential correction steps for Type I ASD patients. The correction of major thoracolumbar/lumbar curve is performed at first and maintained with short rod (Step 2). Interbody fusion is then performed at L4 to S1 to horizontalize L4 and L5 endplate (Step 3), followed by short rod maintenance (Step 4). Finally, long rods are used to adjust the global alignment (Step 5)

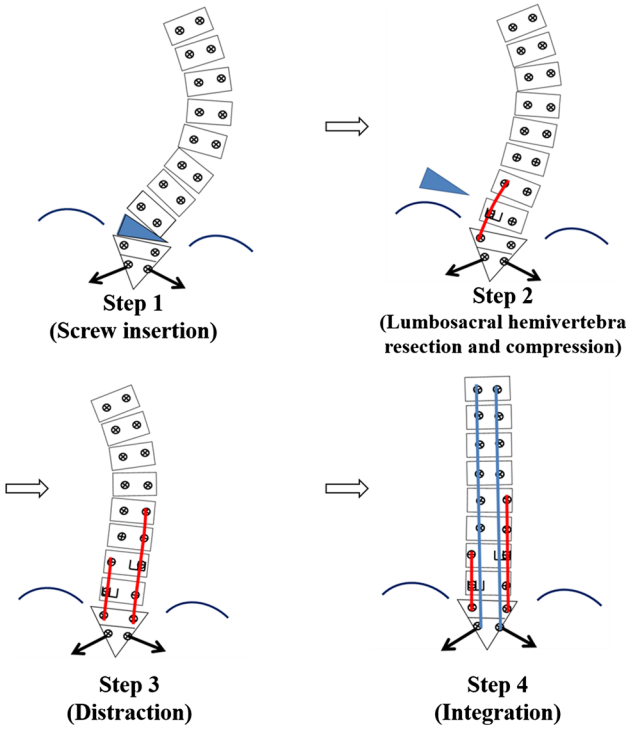

Fig. 3 Schematic diagram of sequential correction steps for Type II ASD patients. Correction of lumbosacral curve is performed at first and maintained with short rod to close the osteotomy site (Step 2). A longer rod is installed at the concave side of lumbosacral curve for distraction (usually from L2 or L3, the vertebra below thoracolumbar apex, Step 3). Finally, long rods are used to adjust the global alignment (Step 4)

are inserted from the UIV to pelvis to correct remaining coronal and sagittal imbalance and to achieve solid spino-pelvic fixation. Local bone graft is also placed for sound fusion. The long rods are integrated with short rods using cross-links, Dominos or connectors with two tulips.

Study cohort

This is a retrospective analysis of 21 ASD patients undergoing sequential correction from May 2015 to May 2017. The study has been approved by the Clinical Research Ethics Committee of the hospital. All patients were resistant to active non-surgical treatments (medications, exercise and bracing) for a minimum of 1 year. Inclusion criteria were as follows: ASD patient undergoing sequential correction, with S2AI screws and with instrumentations extended to T10 or above. Patients with prior spine surgery, spinal neoplasms or spinal tuberculosis were excluded.

Evaluation of surgical outcomes

Long-cassette standing anteroposterior radiographs of the entire spine were obtained at baseline and 2 weeks postoperatively. On coronal films, major Cobb angle and GCM, defined as the horizontal distance between C7 plumb line (C7PL) and central sacral vertical line, were measured. On sagittal films, classic sagittal spino-pelvic parameters were measured, including pelvic incidence (PI), pelvic tilt (PT), sacral slope (SS), lumbar lordosis (LL), thoracic kyphosis (TK), sagittal vertical axis (SVA) and T1 pelvic angle (TPA).

All measurements were performed using Surgimap Software (Surgimap Spine Software, version 2.2.9, New York, USA).

According to Qiu coronal classification [7], three types of global coronal malalignment were determined: Type A: GCM ≤ 3 cm; Type B: GCM > 3 cm and C7PL shifts to the concave side of the curve; and Type C: GCM > 3 cm and C7PL shifts to the convex side of the curve.

Statistical analysis

The data were analyzed using statistical software (SPSS 20.0, SPSS Inc., Chicago, IL). Statistical data are presented as the mean ± standard deviation. Comparisons between baseline and post-op parameters were made by paired *t* test. A p value < 0.05 was considered statistically significant.

Results

For the 21 patients (3 males and 18 females), the mean age was 51.9 ± 8.12 years. Demographical and radiological measurements of the patients are summarized in Table 1. The mean Cobb angle was 54.13° ± 19.83°, and the mean baseline GCM was 2.90 ± 1.74 cm. In total, 14 of the 21 patients were the Type I ASD and 7 patients were Type II ASD patients. The age, gender and the severity of the baseline GCM showed no significant difference between the two types ($p = 0.647$, 0.721 and 0.135, respectively). The Cobb angle of Type II patients was significantly larger than that in Type I group (50.48° vs. 61.42°, $p < 0.001$).

Both coronal and sagittal alignments were analyzed in the study to evaluate the surgical outcomes. In coronal plane, both Cobb angle and GCM were significantly improved after surgery (Table 1). In Type I patients, Cobb angle was improved from 50.48° to 26.91° and maintained at 29.52° at the latest follow-up. GCM was improved from 2.94 to 0.95 cm and changed to 1.21 cm at follow-up; in Type II patients, Cobb angle was improved from 61.42° to 28.48°, and GCM was improved from 2.82 to 1.38 cm and maintained as 1.56 cm at follow-up. The patients were also stratified based on Qiu coronal classification: 11 patients were Qiu Type A, 3 patients were Qiu Type B and 7 patients were Qiu Type C. In detail, 9 Type I and 2 Type II patients were Qiu Type A, 3 Type I patients were Qiu Type B, 2 Type I and 5 Type II patients were Qiu Type C. After surgery, only 1 patient in Type II group with baseline Qiu Type C GCM did not achieve coronal balance; the rest 20 patients were all changed to or maintained as Qiu Type A (Table 2).

Regarding sagittal alignment, PT, LL, PI-LL and SVA were all significantly improved after surgery and maintained at follow-up in both Type I and II patients. Post-op PI-LL was 13.42° in Type I patients and 14.08° in Type II patients, and SVA was 15.31 mm and 28.32 mm, respectively; it was 14.27 mm and 31.48 mm at 3 months after surgery, demonstrating satisfactory sagittal alignment restoration. Regarding the major complication, one patient experienced

Table 1 Different demographical and radiographic parameters of patients in sequential correction Type I and sequential correction Type II with adult spinal deformity (ASD)

			Type I			Type II
Number			14			7
Age			52.6 (7.61)			50.7 (7.83)
Gender M:F (% of F)			2:12 (85.71)			1:6 (85.71)
	Pre-op	Post-op	Latest follow-up	Pre-op	Post-op	Latest follow-up
Cobb (°)	50.48 (20.64)	26.91 (13.95)	29.52 (16.48)	61.42 (15.76)	28.48 (6.69)	30.76 (8.73)
GCM (cm)	2.94 (1.88)	0.95 (0.42)	1.21 (0.57)	2.82 (1.73)	1.38 (0.63)	1.86 (0.82)
Number of GCM patients	5	0	0	5	1	1
PT (°)	24.71 (9.89)	20.36 (10.48)	22.54 (11.25)	28.65 (10.77)	20.52 (8.43)	21.29 (11.71)
PI (°)	44.28 (19.74)	42.32 (16.60)	43.14 (13.79)	35.39 (20.77)	33.29 (15.27)	34.87 (13.66)
SS (°)	19.57 (15.52)	21.96 (7.45)	20.60 (10.12)	6.74 (26.39)	12.77 (11.94)	13.58 (12.40)
LL (°)	6.37 (29.94)	28.90 (10.98)	30.25 (13.43)	– 10.30 (32.44)	19.21 (16.42)	21.16 (14.03)
PI-LL (°)	37.91 (23.53)	13.42 (10.53)	12.89 (11.19)	45.69 (14.55)	14.08 (8.44)	13.71 (5.48)
TK (°)	6.77 (24.86)	18.21 (8.26)	17.57 (9.83)	11.78 (20.65)	24.62 (10.55)	21.58 (8.89)
SVA (mm)	27.07 (80.34)	15.31 (19.20)	14.27 (15.97)	73.13 (64.34)	28.32 (34.45)	31.48 (42.07)
TPA (°)	25.77 (10.46)	13.46 (10.99)	15.74 (11.28)	30.63 (14.25)	13.30 (8.06)	14.81 (9.72)

Data presented as mean values with standard deviations

PT pelvic tilt, *PI* pelvic incidence, *SS* sacral slope, *LL* lumbar lordosis, *PI-LL* pelvic incidence minus lumbar lordosis, *TK* thoracic kyphosis, *SVA* sagittal vertical axis, *TPA* T1 pelvic angle, *GCM* global coronal malalignment

Table 2 Different demographical and radiological parameters of patients in Type A, Type B and Type C using Qiu coronal classification and mean values with standard deviations

	Type A	Type B	Type C	*p* value
Pre-op number	11	3	7	–
Age	48.6 (8.01)	51.3 (7.66)	56.8 (7.30)	0.519
Gender M:F (% of F)	2:9 (81.82%)	1:2 (66.67%)	0:7 (100%)	
Cobb angle (°)	55.42 (21.6)	74.8 (13.6)	54.72 (12.08)	0.633
Pre-op GCM (cm)	1.53 (0.50)	3.50 (0.26)	5.15 (1.27)	0.019
Post-op GCM (cm)	0.95 (0.42)	1.85 (0.35)	1.38 (0.63)	0.537
Post-op number	20	0	1	

Independent t-test

GCM global coronal malalignment

unexpected rod breakage (the long rod installed at the last step) at 6-month follow-up, and we did not perform a revision surgery since the regional and global alignment did not change after rod breakage.

Discussion

Although coronal imbalance was viewed as a manifestation of adult spinal deformity, current treatment guidelines most commonly highlight sagittal malalignment, whereas the coronal alignment has been relatively overlooked. Recently, several research teams have started focusing on the high incidence of postoperative global coronal malalignment which may be related to the surgical maneuvers. In the current study, we set up a flow of surgical procedures to ensure the adequate coronal realignment, and the surgical outcomes showed satisfactory GCM restoration. The incidence of postoperative GCM in ASD patients could be as high as 30% in previous literatures [7]. In this study, the incidence was 4.7%, showing a high reduction from the traditional correction techniques. Particularly, only 1 baseline Qiu Type C patients remained Qiu Type C GCM after surgery, demonstrating the satisfactory clinical outcome using sequential correction technique.

The main philosophy of sequential correction technique is to divide the complex deformity correction procedures into different steps. Each step contains one or two maneuvers and focuses only on one task. Therefore, the surgeons could break down the complex surgery into several simple surgical procedures which are easier to perform. In traditional correction techniques, the installation of rods is difficult even after correction since only two rods are used to control both segmental curve and global alignment. If the rods are pushed too hard for fitting the screws (even with the multi-axial pedicle screws), the global coronal alignment sometimes cannot be maintained, and the biomechanical stress would increase. With the sequential correction, the segmental curves are corrected and fixed with segmental rods; therefore, the two long rods are only responsible for controlling global alignment. In the primary thoracolumbar/lumbar ASD (Type I) patients, the step of correction is performed at first to address the primary cause of spinal deformity. At the correction step, a short rod is used to close the osteotomy site and to correct both scoliosis and kyphosis. The second step of leveling is to address the compensatory lumbosacral curve (the fractional curve). We recommend here to use L4-S1 TLIF with additional L4-S1 PCO to horizontalize the L5 and L4 upper endplates which serve as the foundation of the spine. Appropriate correction of fractional curve could decrease the risk of iatrogenic global coronal malalignment in ASD patients. It should be noted that the L4-S1 TLIF cage is recommended to be inserted from the convex side of the LS curve since the convex side provides larger space to insert the cage and is easier to perform the following compression maneuver. In ASD patients with primary lumbosacral curve (Type II), the first correction step also focuses on the primary cause of the deformity; thus, the LS bony abnormity is resected at first. L5 horizontalization should also be emphasized as the foundation of coronal spinal alignment. Next, distraction maneuver is performed at the contralateral side to push the lumbar segments to the middle line. The decomposed surgical procedures could reduce the difficulty of rod installation since the deformity is corrected step by step.

The multi-rod construct is the foundation of sequential correction. With multiple rods, the spine can be stabilized after each surgical step and the final biomechanical property is also superior compared to traditional two-rod instrumentations [11]. The multi-rod construct also disperses the stress of each rod at the osteotomy site and/or lumbosacral region, and creates a gradual transition zone from osteotomy area (stress concentration area) to non-instrumented region. Luca et al. reported with finite element models that the multi-rod constructs could significantly reduce the stresses on the spinal fixators at the 3CO site [12]. Merrill et al. also demonstrated in ASD patients that the multi-rod constructs can prevent rod breakage and pseudarthrosis at the lumbosacral junction compared to traditional two-rod constructs [13]. In this sequential correction technique, we use special connectors with two tulips as the anchors for the multi-rod constructs. If the special connectors with two tulips are not available, Dominos can be an alternative option.

Pelvic fixation is recommended for ASD patients undergoing sequential correction due to the correction of fractional curve. We prefer S2AI screws for pelvic fixation due to the low-profile and less soft tissue dissection. In terms of biomechanics, S2AI screws can purchase tricortical

layers, namely bicortical layers of the sacrum and a monocortical layer of ilium, whereas iliac screws typically have mono- or bicortical purchase of ilium. Ishida et al. reported that the S2AI technique demonstrated a lower rate of overall reoperation, a similar rate of PJK, longer time to reoperation comparing to iliac screws for ASD patients [14]. The same team also demonstrated that S2AI screws were associated with few complications [15]. Hoernschemeyer et al. [16] showed in a biomechanical study that the S2AI screws are as stable as iliac screws with biomechanical testing in flexion, extension, rotation, lateral bending and axial rotation. Recently, a cross-sectional study carried out by Cecchinato et al. [17] has reported that PI decreased during the early postoperative in adult spinal deformity patients who underwent long fusion to the sacrum with pelvic fixation. Tseng et al. reported that PI decreased in 55% of ASD patients after spinal deformity surgery using S2AI screws [18]. Our data also showed similar trend of decreased PI in Type I patients who are mainly degenerative scoliosis (Table 1). According to previous report [19], decrease in PI may be attributed to the laxity of the sacroiliac joint, but this theory requires more solid evidence.

Despite the promising findings of our series, we recognize that this study presents several shortcomings. First, this small group of patients has some inherent selection bias. Nonetheless, the same senior surgeon operated on all patients, using a well-standardized procedure. Second, our minimum follow-up of 1 year is too short to assess the integrity of fusion; a longer follow-up is necessary to determine the maintenance of spinal alignment. Our objective was to report the technical feasibility, clinical results of coronal alignment restoration and early mechanical or general complications using this technique. The presented data did not focus on the functional results, as previous studies have documented a high satisfaction rate among ASD parents after correction. Further studies, on a larger group of patients, are needed to explore long-term functional results of this technique compared to other procedures.

Conclusion

In this study, we described a new technique of sequential correction for ASD patients. It allows one to decompose the complex correction surgery into several easier steps, and each step focuses on only one task. It can also reduce the difficulty of rod installation due to the separated surgical maneuvers and the use of multi-rod system. The technique could help to restore the global coronal alignment compared to traditional techniques. The incidence of postoperative coronal GCM was 4.7% after sequential correction.

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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