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Clinical Study

Does solid fusion eliminate rod fracture after pedicle subtraction osteotomy in ankylosing spondylitis-related thoracolumbar kyphosis?

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Abstract

BACKGROUND CONTEXT: Rod fracture (RF) has a negative impact on the surgical outcome of patients with ankylosing spondylitis (AS) after lumbar pedicle subtraction osteotomy (PSO). However, there is a paucity of published studies analyzing the risk factors for RF in PSO-treated patients with AS with thoracolumbar kyphosis.

PURPOSE: The objective of this study was to investigate the risk factors for RF after PSO for thoracolumbar kyphosis secondary to AS.

STUDY DESIGN/SETTING: This is a retrospective single-center study.

PATIENT SAMPLE: Patients with AS who underwent PSO for thoracolumbar kyphosis between January 2002 and December 2016 were included.

OUTCOME MEASURES: Demographic data, including age, sex, body mass index, and smoking status, were summarized. The surgical data analyzed included the levels of osteotomy, the fusion levels, the upper instrumented vertebra, the lower instrumented vertebra, the osteotomy site, the rod material, the rod diameter, and the rod contour angle (RCA). Radiographic parameters included the sagittal vertical axis, thoracic kyphosis, lumbar lordosis, sacral slope, pelvic tilt, and pelvic incidence. Radiographic parameters were measured at baseline, immediately after the operation, and at the final follow-up. Adequate ossification of the anterior longitudinal ligament (ALL) at the PSO level was defined by a total bony bridge. Adequate ossification of the ALL was also measured at baseline, immediately after the operation, and at the final follow-up.

METHODS: Patients with a minimum of 2 years' follow-up or patients who developed RF were enrolled in the study. Recruited patients were divided into the RF group and the no-RF group based on whether they developed RF. Patient demographics, operative data, radiographic parameters, and adequate ossification of the ALL were analyzed to determine the risk factors for RF. For patients with RF, the fusion status at the PSO level, the time course to the development of RF, the site of RF, and the corresponding solution were also recorded.

RESULTS: Rod fracture occurred in 11 (8.9%) of the 123 recruited patients. Solid fusion at the PSO level was found in all patients in the RF group. The average duration to the onset of RF was 31.4 months (range, 12–68 months). All RFs occurred at or immediately adjacent to the PSO level. The RCA was greater in the RF group than in the no-RF group (27.8° vs 22.9°, p=.031). A greater proportion of patients with a rod diameter of 5.50 mm were found in the RF group than in the no-RF group (100.0% vs 68.8%, p=.033). There was a larger proportion of patients with adequate ossification of the ALL at the final follow-up visit in the no-RF group than in the RF group (67.0% vs 27.3%, p=.018). Multivariate analyses demonstrated that the RCA (odds ratio, 1.174; 95% confidence interval, 1.018–1.354; p=.028) and adequate ossification of the ALL at the final follow-up visit (odds ratio, 0.079; 95% confidence interval, 0.014–0.465; p=.005) were independent factors for

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RF. Notably, revision surgery was performed among six patients, whereas conservative treatment was used for the remaining five patients.
CONCLUSIONS: In patients with AS after PSO for thoracolumbar kyphosis with solid fusion at the PSO level, the incidence of RF was 8.9%. Rod diameter was identified as a risk factor for RF. Furthermore, the RCA was identified as an independent risk factor for RF. In contrast, adequate ossification of the ALL around the PSO level at the final follow-up visit was identified as an independent protective factor for RF.

Keywords: Ankylosing spondylitis; Bone union; Pedicle subtraction osteotomy; Risk factors; Rod fracture; Thoracolumbar kyphosis

Introduction

Ankylosing spondylitis (AS) is a chronic inflammatory disease that commonly affects the spine [1]. Changes in the spine are characterized by progressive rigidity and deterioration of the sagittal malalignment, and the stiffening of the spine is always caused by the ossification of facet joints and the formation of syndesmophytes [2]. In the advanced stages of AS, severe spinal sagittal deformity is often associated with stooped posture and an inability to look straight ahead [1]. Spinal deformity correction surgery is required to restore the sagittal alignment and the capacity to see the horizon.

Pedicle subtraction osteotomy (PSO) [3] has proven to be efficient, safe, and suitable for treating patients with advanced AS with severe thoracolumbar kyphosis [4,5]. Despite satisfactory surgical outcomes of PSO, concerns remain about the overall complications [6], such as proximal junctional kyphosis, loss of correction, and instrumentation failure. Specifically, postoperative rod fracture (RF) appears to be the most common phenomenon in the case of instrumentation failure. The incidence of RF in PSO-treated adult spinal scoliosis (ASD) patients varies from 15.8% to 22.0% [7,8]. Older age, higher body mass index (BMI), greater baseline sagittal malalignment, residual postoperative sagittal malalignment, a high-degree rod contour angle (RCA), and pseudarthrosis have been identified as risk factors for RF. Anterior interbody support, plenty of autogenous or allograft bone, and supplemental satellite rods are currently considered to be helpful in protecting rods from fracture. However, few articles have documented the risk factors for RF in patients with AS. Therefore, the present study investigated the incidence, risk factors, and corresponding solutions for RF in PSO-treated patients with AS with thoracolumbar kyphosis.

Methods

Patient population

The present study was a single-center retrospective review of patients with AS with thoracolumbar kyphosis treated using PSO between January 2002 and December 2016. All patients were diagnosed with AS using the Modified New York Criteria [9]. Inclusion criteria were as follows: (1) age older than 20 years at the time of surgery and (2) availability of full-length standing radiographs at follow-up. Exclusion criteria were as follows: (1) prior spinal surgery, (2) surgery for spinal fracture, and (3) postoperative coronal imbalance (a coronal plane curve greater than 10°). All patients were followed up for more than 2 years or until they developed RF. The surgical plan was made mainly according to the lateral radiographs with the aims of maintaining horizontal gaze and restoring a balanced, upright posture. If the amount of correction required was approximately 35°, closing wedge osteotomy was recommended. When the needed correction angle was more than 35° but less than 60°, deformity correction could be achieved by transforming the closing wedge osteotomy into a closing-opening wedge osteotomy [10]. Furthermore, the sagittal realignment with the required correction angle of more than 60° was accomplished through the two-level PSO [11]. Pedicle subtraction osteotomy was mostly performed at the apex of the kyphosis. The extension of fixation routinely covered four levels cephalad to the osteotomized vertebra and three levels caudal to the osteotomized vertebra. Patients were classified into the RF and the no-RF groups, depending on whether they developed RF. Rod fracture diagnoses were based on follow-up radiographs. The current study was approved by the institutional review board.

Data collection

Demographic, surgical, and radiographic data were obtained for recruited patients. Demographic data included age, sex, BMI, and smoking status. Surgical data included the levels of the osteotomy (one- or two-level PSO), the fusion levels, the upper instrumented vertebra (UIV) level, the lower instrumented vertebra (LIV) level, the osteotomy site in one-level PSO, the rod material, the rod diameter, and the RCA. Because of the limited number of patients who underwent two-level PSO (seven patients had two-level PSOs at L1 and L4, whereas the remaining six patients had two-level PSOs at L2 and L5), the amount of patients was too small to detect the effect of osteotomy sites on RF using statistical analysis. Therefore, the effect of osteotomy sites on RF was not analyzed among the two-level PSOs. UIV was divided into levels above T9 or below T10, and LIV was divided into levels above L5 or at S1 according to the thoracolumbar and lumbosacral junctions, respectively. Freestanding anteroposterior and lateral spine radiographs taken before the operation, immediately after the operation, and at the final follow-up visit

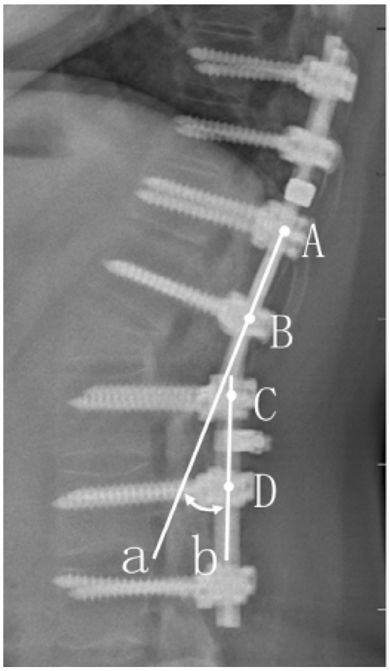

Fig. 1. A lateral radiograph of the spine showing the measurement of the RCA. Line a represents the line connecting the centers of the heads of the two screws inserted into the two vertebrae cephalad to the vertebra of osteotomy (Points A and B). Line b represents the line linking the centers of the heads of the two screws inserted into the two vertebrae caudal to the vertebra of osteotomy (Points C and D). The RCA is defined as the angle formed by Lines a and b. RCA, rod contour angle.

were analyzed using Surgimap software (Nemaris, New York, NY, USA). The RCA was measured at the PSO level on immediate postoperative radiographs using the lines connecting the heads of the two screws inserted into the two vertebrae cephalad and caudal to the vertebrae undergoing the osteotomy (Fig. 1). For patients who underwent two-level PSO, the RCA with the larger degree was used for the analysis. In the sagittal spinal alignment analysis, the radiographs from the visit before RF were used as the final follow-up radiographs in patients with RF to eliminate the influence of RF on sagittal parameters. The radiographic parameters included (1) the sagittal vertical axis (SVA) [10]: the horizontal distance from the C7 plumb line to the posterosuperior corner of the S1 vertebra (the SVA was positive if the C7 plumb line fell anterior to the sacrum; otherwise, it was negative); (2) thoracic kyphosis [10]: the angle measured from the upper end plate of T4 to the lower end plate of T12 (the angle was positive when the curve was kyphotic and negative when the curve was lordotic); (3) lumbar lordosis (LL) [10]: the angle formed by the upper end plate of L1 and the upper end plate of S1 (the angle was positive for the kyphotic segment and negative for the lordotic segment); (4) the pelvic tilt [10]: the angle between the line through the midpoint of the sacral plate to the femoral head axis and the vertical axis; (5) the sacral slope [10]: the angle between the sacral plate and the horizontal axis; and (6) the pelvic incidence [10]: the angle created by the perpendicular line to the midpoint of the sacral plate and the line from the center of the femoral heads to the midpoint of the sacral plate. Adequate ossification of the anterior longitudinal ligament (ALL) at the PSO level was defined as the formation of a total bony bridge at the anterior corners of all four sites adjacent to the PSO level according to the modified Stoke Ankylosing Spondylitis Spine Score (mSASSS) [12]. For patients who underwent two-level PSO, adequate ossification of the ALL was only measured at the PSO level with the larger degree of the RCA. Radiographic parameters and adequate ossification of the ALL were measured at baseline, immediately after the operation, and at the final follow-up visit. For each patient with RF, the time course to RF, the site of RF, and the fusion status at the osteotomy site were also recorded. Fusion status was determined based on serial follow-up radiographs. Solid fusion at the PSO level was defined as the absence of a persistent lucent line with the presence of continuous trabecular bone across the level [13]. In patients who underwent revision surgery, surgical exploration was performed to confirm the fusion status, and details of the revision surgical procedure were reviewed.

Statistical analysis

All data analyses were performed using SPSS 18.0 software (SPSS, Chicago, IL, USA). Student *t* tests were used to assess differences in continuous variables. Chi-square tests were used to analyze differences in categorical data with more than five observations. Fisher exact test was used to analyze categorical data with less than less observations. A p-value less than .05 was considered statistically significant. All variables with p-values less than .15 were included in the stepwise multivariate analysis. Variables with p-values less than .05 were identified as independent factors for RF.

Results

Patient population

A total of 123 consecutive patients with AS after PSO were included in the current study. Thirty-five patients were treated with cobalt chromium rods, whereas the remaining 88 patients were treated with titanium alloy rods. Rod fracture occurred in 11 of the 123 patients (8.9%). In five patients, RF was found incidentally on routine follow-up radiographs and did not present any symptoms. However, the remaining six patients with RF returned to our center with chief complaints of back pain and a prominence at the surgical site. Rod fracture was confirmed on the radiographs. Of the 11 patients with RF, 10 were treated with one-level PSO, whereas 1 underwent two-level PSO. The mean time interval between the initial surgery and the onset of RF was 31.4 months (range, 12–68 months). All 11 patients had solid fusion at the osteotomy site, which was confirmed in six patients during revision surgery. Unilateral RF was observed in six patients, whereas development of bilateral RF was observed in the remaining patients. Almost all RFs occurred at the PSO level, except for one at the Site 1 level caudal to the

Table 1
Comparison of baseline patient demographics between the two groups*

	RF (n=11)	No-RF (n=112)	p-Value
BMI	23.8±4.5	22.5±4.1	.200
Smoking (%)	63.6	39.3	.198
Sex (male, %)	100.0	85.7	.357
Age (y)	32.6±8.6	35.9±10.0	.287

RF, rod fracture; BMI, body mass index.
* Data are presented as mean values±standard deviation.

PSO level in the patient who underwent two-level PSO with a bilateral RF.

Assessment of risk factors

Comparison of the patient demographics between the two groups is presented in Table 1. There were no statistically significant differences in BMI, smoking status, sex distribution, or age between the two groups. The result of the data analysis evaluating the impact of surgical factors on the development of RF is shown in Table 2. The RCA was larger in the RF group than in the no-RF group (27.8° vs 22.9°, p=.031). The type of rod composition, the fusion levels, the UIV level, the LIV level, the osteotomy site in one-level PSO, and the performance of two-level PSO were not associated with the RF.

Comparison of the preoperative, the immediate postoperative, and the follow-up sagittal parameters between the two groups is shown in Table 3. After PSO, LL was restored significantly in both the RF and the no-RF groups (0.6° vs –49.6°,

Table 2
Comparison of surgical factors between the two groups*

	RF (n=11)	No-RF (n=112)	p-Value
Fusion levels	9.0±1.4	8.6±2.0	.510
UIV level (%)			1.000
Above T9	36.4	42.0	
Below T10	63.6	58.0	
LIV level (%)			1.000
L5 or above	72.7	72.3	
Sacrum	27.3	27.7	
Double-level PSO (%)	9.1	10.7	1.000
Single-level PSO (osteotomy site, %)			.153
L1	0	25.0	
L2	72.7	50.9	
L3	18.2	13.4	
Rod material (%)			.291
TA	54.5	73.2	
CC	45.5	26.8	
Rod diameter (%)			**.033**
5.50 mm	100.0	68.8	
6.35 mm	0	31.3	
RCA (°)	27.8±5.1	22.9±7.4	**.031**

RF, rod fracture; UIV, upper instrumented vertebra; LIV, lower instrumented vertebra; PSO, pedicle subtraction osteotomy; TA, titanium alloy; CC, cobalt chromium; RCA, rod contour angle.
* Data are presented as mean values±standard deviation. Bold type represents statistical significance.

Table 3
Comparison of the preoperative, the immediate postoperative, and the latest follow-up radiographic parameters between the two groups*

Radiographic parameters	RF (n=11)	No-RF (n=112)	p-Value
SVA (mm)			
Baseline	174.3±75.7	175.9±70.2	.944
After PSO	32.4±44.6	44.4±46.8	.414
Change after PSO	141.9±56.7	131.4±58.1	.568
p-Value†	**<.001**	**<.001**	–
Latest follow-up	35.5±30.5	45.9±47.3	.474
Change during the follow-up	−3.1±34.2	−1.5±39.6	.897
p-Value‡	.771	.692	—
TK (°)			
Baseline	41.0±11.3	49.8±18.6	.128
After PSO	43.2±12.4	49.1±16.5	.248
Change after PSO	−2.2±3.4	0.7±9.7	.330
p-Value†	.059	.443	—
Latest follow-up	45.7±11.2	48.8±15.5	.527
Change during the follow-up	−2.5±5.7	0.3±9.0	.303
p-Value‡	.167	.699	—
LL (°)			
Baseline	0.6±21.4	0.9±21.7	.962
After PSO	–49.6±10.7	–47.2±15.4	.619
Change after PSO	50.1±17.9	48.0±17.5	.712
p-Value†	**<.001**	**<.001**	—
Latest follow-up	–44.1±7.4	–44.0±13.7	.979
Change during the follow-up	−5.5±5.6	−3.2±8.4	.380
p-Value‡	**.009**	**<.001**	—
SS (°)			
Baseline	4.6±12.5	8.1±11.5	.333
After PSO	25.3±6.8	24.3±10.2	.753
Change after PSO	−20.7±9.8	−16.2±9.1	.118
p-Value†	**<.001**	**<.001**	—
Latest follow-up	20.3±6.4	21.8±9.4	.600
Change during the follow-up	5.0±5.7	2.5±6.1	.190
p-Value‡	**.015**	**<.001**	—
PT (°)			
Baseline	40.2±8.3	37.4±11.0	.421
After PSO	19.9±8.8	21.2±10.4	.701
Change after PSO	20.3±7.0	16.3±8.0	.112
p-Value†	**<.001**	**<.001**	—
Latest follow-up	23.9±9.1	24.2±9.8	.928
Change during the follow-up	−4.0±3.5	−3.0±5.8	.595
p-Value‡	**.003**	**<.001**	—
PI (°)			
Baseline	44.7±11.5	45.7±11.5	.798
After PSO	45.2±8.2	45.5±11.2	.927
Change after PSO	−0.5±4.6	0.2±6.4	.757
p-Value†	.751	.791	—
Latest follow-up	44.2±9.2	46.0±11.0	.593
Change during the follow-up	1.0±3.0	−0.5±4.5	.272
p-Value‡	.300	.216	—

RF, rod fracture; PSO, pedicle subtraction osteotomy; SVA, sagittal vertical axis; TK, thoracic kyphosis; LL, lumbar lordosis; SS, sacral slope; PT, pelvic tilt; PI, pelvic incidence.
* Data are presented as mean values±standard deviation. Bold type represents statistical significance. Change after PSO was calculated as the baseline value minus the value after PSO; change during follow-up was calculated as the value after PSO minus the latest follow-up value.
† The p-value represents paired *t* test comparison between the baseline value and the value after PSO.
‡ The p-value represents paired *t* test comparison between the value after PSO and the latest follow-up value.

Table 4
Comparison of proportion of patients with adequate ossification of the anterior longitudinal ligament between the two groups at baseline, immediately after PSO, and at the latest follow-up*

	RF (n=11)	No-RF (n=112)	p-Value
Baseline (%)	18.2	29.5	.727
After PSO (%)	18.2	29.5	.727
Latest follow-up (%)	27.3	67.0	**.018**

RF, rod fracture; PSO, pedicle subtraction osteotomy.
* Bold type represents statistical significance.

p<.001, and 0.9° vs –47.2°, p<.001). No significant difference was observed in the amount of correction in the SVA (141.9 mm vs 131.4 mm, p=.568), thoracic kyphosis (–2.2° vs 0.7°, p=.330), LL (50.1° vs 48.0°, p=.712), sacral slope (–20.7° vs –16.2°, p=.118), or pelvic tilt (20.3° vs 16.3°, p=.112) between the two groups. During follow-up, a correction loss in LL was found in both the RF and the no-RF groups (–49.6° vs –44.1°, p=.009, and –47.2° vs –44.0°, p<.001). However, no significant correction loss in the SVA was observed in either the RF or the no-RF group (32.4 mm vs 35.5 mm, p=.771, and 44.4 mm vs 45.9 mm, p=.692). No sagittal measurement was related to the development of RF.

Comparison of adequate ossification of the ALL between the two groups is presented in Table 4. At baseline, there was no significant difference regarding the proportion of patients with adequate ossification of the ALL between the RF and the no-RF groups (18.2% vs 29.5%, p=.727). However, at the final follow-up visit, there was a greater proportion of patients with adequate ossification of the ALL in the no-RF group than in the RF group (67.0% vs 27.3%, p=.018).

The result of the stepwise multivariate regression analysis of the variables associated with RF is shown in Table 5. The RCA was identified as an independent risk factor for RF (odds ratio, 1.174; 95% confidence interval, 1.018–1.354; p=.028), whereas adequate ossification of the ALL at the final follow-up visit was identified as an independent protective factor for RF (odds ratio, 0.079; 95% confidence interval, 0.014–0.465; p=.005).

After a comprehensive assessment of each patient with RF, observations were suggested for the five asymptomatic patients with RF. For the six symptomatic patients who underwent revision surgery, the broken rods were relinked with domino connectors in one patient and supplemented with satellite rods spanning the PSO level in another. The bilateral rods of the four remaining patients were replaced with new, intact rods; satellite rods were also used. In the six patients who underwent revision surgery, no pseudarthrosis or posterior column gap at the PSO level was found through surgical exploration.

Table 5
Multivariate analysis of variables associated with RF*

	Odds ratio	95% Confidence interval	p-Value
RCA (°)	1.174	1.018–1.354	**.028**
Formation of total ossification of ALL at the latest follow-up	0.079	0.014–0.465	**.005**

RF, rod fracture; RCA, rod contour angle; ALL, anterior longitudinal ligament.
* Data are presented as mean values±standard deviation. Bold type represents statistical significance.

Discussion

This single-center retrospective study assessed the incidence of and the risk factors for RF in patients with AS after PSO. Rod fracture in ASD commonly occurs in the context of pseudarthrosis in the absence of mechanical stability [14]. However, in the current study, no pseudarthrosis was observed in the RF group, and the RF incidence was 8.9% with a mean interval of 31.4 months (range, 12–68 months). In two previous studies on ASD after PSO, the rates of RF were 15.8% and 22.0%, and the time courses to RF were 10 and 14 months [7,8]. The lower incidence of RF and the longer interval to RF in the current study may be attributed to solid fusion at the PSO site. Solid fusion at the PSO level without the development of pseudarthrosis may be attributed to the predominant ability of bone healing in AS. As reported, no bone non-unions were found at the osteotomy site because of the superior fusion capacity in AS and the correction of kyphosis [15,16]. Compared with ASD, solid fusion decreased the rate of RF in AS, although it was not guaranteed that patients would not experience RF. Therefore, other factors related to RF should be the main priority. In the current study, the RCA, the rod diameter, and the proportion of patients with adequate ossification of the ALL at the final follow-up visit were significantly different between the RF and the no-RF groups.

Almost all of the RF locations presented at the osteotomy level, except for one that was adjacent to the osteotomy level (Fig. 2D). This finding may have been caused by discontinuity around the PSO vertebra and the notch sensitivity of the rod material. Pedicle subtraction osteotomy was performed with a wedge osteotomy to restore LL. Wide resection of the posterior bony elements was always accompanied by a lack of continuity. Mechanical compromise of the rods would be expected for the discontinuity at the PSO level. To immobilize the osteotomy site, the rods needed to be bent to secure the rods into the screws. From the perspective of notch sensitivity, the fatigue life of rods was markedly shortened for the notch created by the French bender [17,18]. Furthermore, the site of the RF may be a result of the location of maximum stress that presented at the level of the PSO, as has been shown in previous studies [19,20].

Regarding the surgical factors, the RCA and the rod diameter were significantly different between the two groups. Additionally, the RCA was identified as an independent risk factor for RF. A more aggressive bending of the rods was found in the RF group (Fig. 3B). The effect of stress risers on rods would be increased by the larger RCA [21]. Then the fatigue life of rods from the setting of PSO would be decreased by

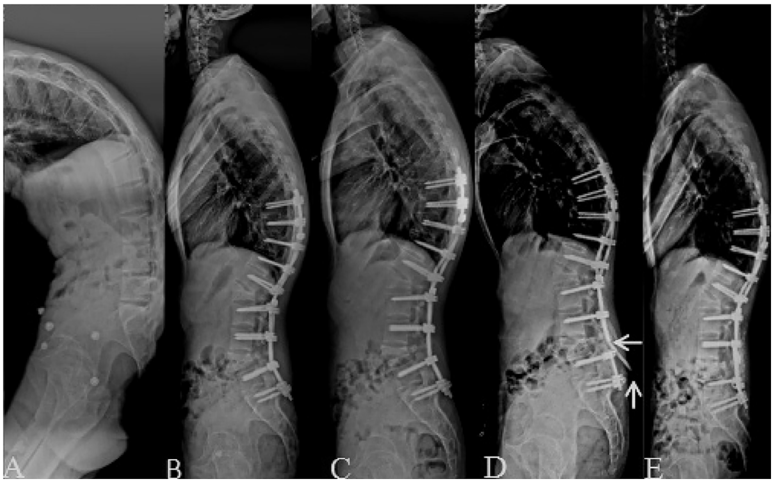

Fig. 2. (A) A 24-year-old man with an SVA of 340 mm. (B) The patient underwent two-level PSO at L1 and L4. The LL improved from 37° to −59° and the SVA improved to 90 mm. The rod contour angles at the L1 and L4 levels were 25° and 27°, respectively. (C) Nine months after surgery, the LL was −58° and the SVA was 98 mm. (D) Two years and 9 months after surgery, the patient developed a rod fracture with the LL aggravated to −40° and the SVA increased to 181 mm. Both rods were fractured (arrows). (E) After revision surgery, the SVA was 92 mm. LL, lumbar lordosis; SVA, sagittal vertical axis.

the larger curve magnitude of the rod contour [22]. For the higher notch sensitivity in titanium alloy and the greater elastic modulus in cobalt chromium [19], there was no difference in the rate of RF between the two types of rods. A greater diameter provides the rods with greater stiffness and resistance to breakage. In our study, all RFs presented in rods with a diameter of 5.5 mm. No RF was found in rods with a diameter of 6.35 mm. This finding suggested that with the achievement of solid fusion at the PSO level in AS, RF might be avoided or at least decreased by the use of rods with a diameter of 6.35 mm. When a larger correction at the PSO site is necessary, the sharp bending of rods could be avoided by using the deep short rod technique [8].

With regard to the sagittal parameters, the two groups showed a mild loss of correction in LL during follow-up. However, SVA was well maintained with pelvic retroversion. No measurement was associated with the development of RF. The result of our study was not consistent with that in a study on ASD that reported that the magnitude of sagittal correction was a causative factor for RF [8]. As the patients after correction surgery tended to return to the preoperative state of sagittal alignment [23], greater stress would be placed on the implants in patients with more aggressive sagittal corrections. However, because the majority of movements in everyday activities were a result of both spine flexion and hip flexion [24], global movements in patients with AS would be achieved by a larger range of motion in hip joints because they would have limited motion in the spine. Benefitting from the limited motion of the spine, the corresponding stress reacted on the instrumented rods would be decreased, which would

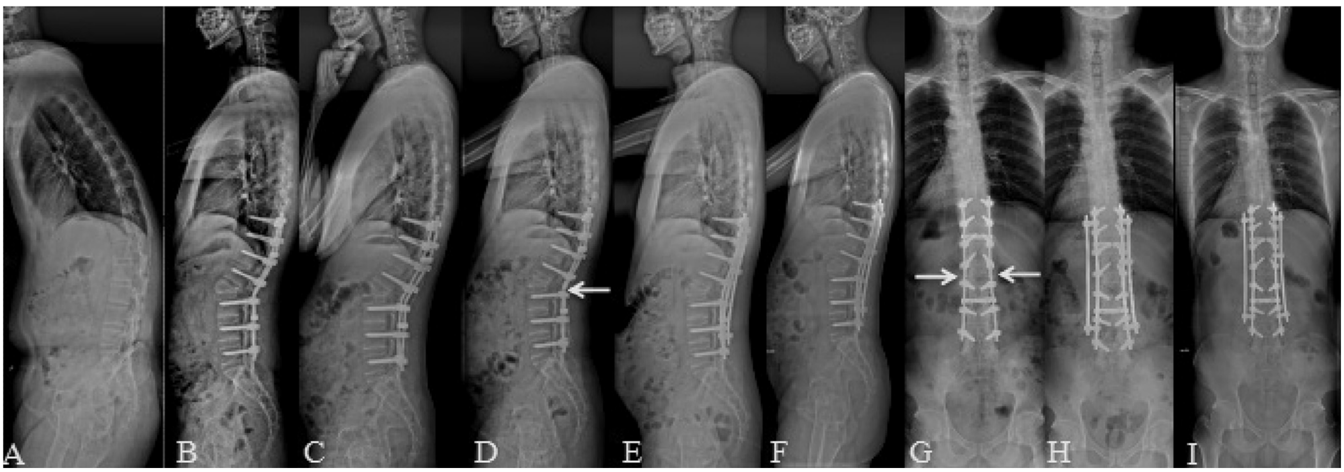

Fig. 3. (A) A 27-year-old man with an SVA of 108 mm. (B) The patient underwent PSO, and the SVA improved to −28 mm and the LL improved from 13° to −44°; the rod contour angle was 29°. (C) Ten months after surgery, the SVA was −14 mm and the LL was −40°. (D and G) Two years and 10 months after surgery, a bilateral rod fracture (arrows) occurred with an SVA of 0. (E and H) After revision surgery, the SVA was 12 mm. (F and I) One year after revision surgery, the SVA was 7 mm. LL, lumbar lordosis; PSO, pedicle subtraction osteotomy; SVA, sagittal vertical axis.

protect the rods from fracture. Because of the rigid spine, the effect of sagittal alignment on RF in AS may not be as strong as it is in ASD. Certainly, we still support that severe post-operative sagittal imbalance would be a risk factor for RF for anteriorly displaced gravity lines placing considerable tension on the implanted rods [7].

Notably, as an independent protective factor for RF, the proportion of patients with adequate ossification of the ALL at the final follow-up visit in the no-RF group was significantly greater than that in the RF group. However, no difference was found between the two groups regarding the proportion of patients with preoperative adequate ossification of the ALL. Ankylosing spondylitis was characterized by the progressive ossification of spinal ligaments over time. In the current study, 43 patients had the formation of adequate ossification of the ALL at follow-up and only 1 patient presented with RF. In contrast with the development of pseudarthrosis during follow-up, adequate ossification of the ALL would provide additional mechanical stability to the osteotomy site, which would protect the rods from fracture. The use of bone morphogenetic protein 2, which was considered to be helpful in decreasing the incidence of RF, highlights the role of mechanical stability in RF as well [8]. The result of the current study confirmed the importance of mechanical stability in the development of RF. More attention should be given to patients who do not show a progression in ossification of the ALL during follow-up.

Fractured rods were replaced with new, intact rods in addition to satellite rods to ensure the mechanical stability of the instrumentation in four patients (Fig. 3E), which was performed in response to the clinical manifestations and images. Satellite rods were placed, spanning the PSO level to supplement the broken rods in the patient with moderate pain and normal sagittal alignment (SVA, 5 mm). In the patient who underwent the two-level PSO, additional satellite rods were not used because successful fixation of implants was achieved without excessive bending of rods (RCA, 17°). Rather, the broken rods were relinked using domino connectors (Fig. 2E).

Three limitations of the present study should be addressed. The 2-year follow-up period may be too short to determine the true incidence of RF. Theoretically, fusion status at the PSO level should be assessed using computed tomography imaging to exclude the development of pseudarthrosis. However, our study did not use computed tomography for the evaluation because of the high radiation dose associated with it. Fusion status was evaluated based on x-rays. Notably, solid fusion was confirmed via surgical exploration for the six patients who underwent revision surgery. Finally, examination of bone mineral density was not routinely performed in the current study because the bone mineral density was unreliable in detecting the osteoporosis in AS for the syndesmophyte formation [25]. Therefore, analysis regarding the effect of bone mass on RF was not available. Future investigations with a longer follow-up period and more comprehensive analyses are certainly warranted.

Conclusions

In AS with solid fusion at the PSO site, the mean time course to RF was 31.4 months, with an RF incidence of 8.9%. The rod diameter was identified as a risk factor for RF. The RCA was also identified as an independent risk factor for RF. In contrast, adequate ossification of the ALL around the PSO level at the final follow-up visit was identified as an independent protective factor for RF.

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