



The Fate of Patients with Adult Spinal Deformity Incurring Rod Fracture After Thoracolumbar Fusion

D. Kojo Hamilton¹, John A. Buza III², Peter Passias², Cyrus Jala², Han Jo Kim³, Tamir Ailon⁴, Munish Gupta⁵, Daniel Sciubba⁶, Amit Jain⁶, Christopher P. Ames⁷, Vedat Deviren⁸, Alan Daniels⁹, Virginie Lafage³, Shay Bess², Eric Klineberg¹⁰, Christopher I. Shaffrey¹¹, Justin S. Smith¹¹, Robert Hart¹², The International Spine Study Group

■ **OBJECTIVE:** To report the outcome of adult spinal deformity (ASD) in patients with rod fracture (RF) after thoracolumbar fusion.

■ **METHODS:** Retrospective review of prospective, multi-center database. Operative patients with ASD ≥18 years old with RF after ASD surgery and with a minimum 6-month follow-up after RF were included. Health-related quality of life scores and radiographic alignment were compared with nonparametric paired and independent testing ($P < 0.05$).

■ **RESULTS:** A total of 51 of 343 patients with ASD (14.9%) sustained a RF, of whom 44 (86.3%) had at least 6-month follow up after RF (mean age = 61.2 years, mean body mass index = 29.6 kg/m²). Mean total follow-up was 37.8 months (range 24.5–66.7 months). Interbody fusion was used in 26 cases of RF (59.1%) (transforaminal lumbar interbody fusion, $n = 17$ [65.4%], anterior lumbar interbody fusion, $n = 5$ [19.2%]). RF was symptomatic in 26 of 44 (59.1%) of patients and discovered incidentally in 18 of 44 patients (40.9%). Overall, 28 RFs were revised (63.6%); 12 of 23 (52.2%) unilateral RF and 16 of 21 (76.2%) bilateral RF at

last follow-up. Revision patients were significantly more likely to be symptomatic at the time of RF detection (78.6% vs. 25.0%, $P = 0.0006$), and had significantly worse Oswestry Disability Index and Scoliosis Research Society-22r pain scores.

■ **CONCLUSIONS:** RFs were detected in 14.9% of patients with ASD and were most common at the L4–L5 and L5–S1 levels. Approximately 63.6% of patients underwent revision surgery. The decision to perform revision surgery may be based predominantly on symptoms referable to the RF, pain, and perceived disability, as radiographic parameters at the time of RF did not differ significantly between patients who did and did not undergo revision.

INTRODUCTION

The treatment of adult spinal deformity (ASD) has advanced markedly over the past decade, with improvements in spinal instrumentation, surgical technique, and

Key words

- Adult spinal deformity
- Health-related quality of life
- Oswestry Disability Index
- Pedicle subtraction osteotomy
- Revision
- Rod fracture

Abbreviations and Acronyms

- 3CO:** Three-column osteotomy
ASD: Adult spinal deformity
BMI: Body mass index
BMP-2: Bone morphogenetic protein-2
HRQL: Health-related quality of life
LL: Lumbar lordosis
NRS: Numeric Rating Scale
ODI: Oswestry Disability Index
PI: Pelvic incidence
PSO: Pedicle subtraction osteotomy
RF: Rod fracture
SF-36: Short-Form-36
SRS-22r: Scoliosis Research Society-22r
SVA: Sagittal vertical axis

From the ¹Department of Neurological Surgery, University of Pittsburgh, Pittsburgh, Pennsylvania; ²Department of Orthopedic Surgery, NYU Langone Orthopedics, New York, New York; ³Department of Orthopaedic Surgery, Hospital for Special Surgery, New York, New York, USA; ⁴Vancouver Spine Surgery Institute, Vancouver General Hospital, Vancouver, Canada; ⁵Department of Orthopedic Surgery, Washington University Orthopedics, St. Louis, Missouri; ⁶Department of Orthopaedic Surgery, Johns Hopkins University, Baltimore, Maryland; ⁷Department of Neurological Surgery, University of California at San Francisco, San Francisco, California; ⁸Department of Orthopaedic Surgery, University of California at San Francisco, San Francisco, California; ⁹Department of Orthopaedic Surgery, Brown University, Providence, Rhode Island; ¹⁰Department of Orthopaedic Surgery, University of California, Davis, Sacramento, California; ¹¹Department of Neurosurgery, University of Virginia, Charlottesville, Virginia; and ¹²Department of Orthopaedic Surgery, Oregon Health and Science University, Portland, Oregon, USA

To whom correspondence should be addressed: D. Kojo Hamilton, M.D.
 [E-mail: KojoHamilton1@gmail.com]

Citation: World Neurosurg. (2017) 106:905-911.
<http://dx.doi.org/10.1016/j.wneu.2017.07.061>

Journal homepage: www.WORLDNEUROSURGERY.org

Available online: www.sciencedirect.com

1878-8750/\$ - see front matter © 2017 Elsevier Inc. All rights reserved.

perioperative care. Although select patients with spinal deformity have the potential for substantial improvement, there are still high rates of complications associated with surgical treatment.¹⁻⁵ One of the most common complications is implant failure, which may be a significant source of patient morbidity.⁶⁻¹⁸ Rod fracture (RF) after surgical treatment of ASD may lead to pain, loss of deformity correction, and the need for revision surgery.^{6,10,19-28}

Risk factors leading to RF have been identified in previous studies and include increasing age, body mass index (BMI), baseline sagittal malalignment, pelvic incidence (PI)—lumbar lordosis (LL) mismatch, greater sagittal alignment correction after surgery, history of previous pedicle subtraction osteotomy (PSO), pseudarthrosis at ≥ 1 -year follow-up, the presence of dominos and/or parallel connectors, and constructs crossing both thoracolumbar and lumbosacral junctions.^{25-29,30} Although risk factors leading up to RF have been explored, less is known about the fate of RF after it occurs. Previous reports have differentiated “clinically significant” or “symptomatic” RF from RF noted incidentally on follow-up radiographs. However, factors that may favor revision versus observation after the development of RF, including development of symptoms, have not been well characterized.

We hypothesized that patients with RF who undergo revision are more likely to be symptomatic at the time of RF detection than patients with RF that do not undergo revision. In addition, we hypothesized that certain patient- and surgery-related factors would be associated with a greater rate of revision surgery, including a history of previous PSO or sagittal malalignment. An improved understanding of treatment and outcomes of patients with ASD after RF could prove valuable for patient counseling and treatment. Our objective was to assess the rate of revision and factors associated with revision based on a prospective, multicenter, consecutive series with a minimum 2-year follow-up.

MATERIALS AND METHODS

This is a retrospective analysis of a prospective, multicenter, consecutive series of patients with ASD treated by members of the International Spine Study Group, which is composed of 11 sites across the United States. Patients were enrolled through a protocol approved by the institutional review boards of the participating sites. Inclusion criteria are patient age > 18 years and presence of at least one of the following measures of spinal deformity: coronal Cobb angle $\geq 20^\circ$, sagittal vertical axis (SVA) ≥ 5 cm, pelvic tilt $\geq 25^\circ$, and thoracic kyphosis $\geq 60^\circ$. Deformities resulting from trauma, neuromuscular disease, spinal infection, ankylosing spondylitis, or tumors are not included in the database. In addition to the database inclusion criteria, patients were included in the present study only if they met the following criteria: 1) ≥ 5 levels of posterior instrumented arthrodesis, 2) availability of baseline full-length standing spine radiographs, 3) development and documentation of RF, and 4) a minimum of 6 months of follow-up subsequent to RF.

Full-length posteroanterior and lateral spine radiographs (36-inch cassette) obtained at baseline, 1-year, and 2-year follow-up were analyzed with the use of validated software (Spineview, ENSAM ParisTech, Paris, France).³¹ All radiographic measurements were performed at a central location based on standard techniques³² and included coronal Cobb angle, thoracic

kyphosis (T4–T12; Cobb angle between the superior endplate of T4 and the inferior endplate of T12), LL (Cobb angle between the superior endplate of L1 and the superior endplate of S1), SVA (C7 plumb line relative to S1), pelvic tilt, and mismatch between PI and LL.

For all patients meeting inclusion criteria, demographic, operative, clinical, and follow-up data were extracted from the database. Extracted data included patient age, sex, BMI, smoking status, and history of previous spine surgery. Primary clinical outcome measures included the Oswestry Disability Index (ODI), Scoliosis Research Society-22r (SRS-22r), Short Form-36 (SF-36), and the Numeric Rating Scale (NRS) score for back, and leg pain. Operative data included levels of spinal instrumented arthrodesis, whether a 3-column osteotomy (3CO) was performed, rod composition and diameter, and grafting material used for arthrodesis, including recombinant human bone morphogenetic protein-2 (BMP-2).

The occurrence of RF and level of fracture were based on review of standardized complication assessment forms that are completed for each patient at each follow-up interval and through review of follow-up full-length radiographs. Data on all RFs were collected and analyzed in the present study, including those that were symptomatic and those detected incidentally. Symptomatic RFs were defined as those in which patients presented with symptoms referable to the site of RF; symptoms included pain, prominence at the surgical site, and/or worsening spinal deformity with loss of correction. The management of RFs was determined based on a review of complication-reporting forms and standardized revision surgery forms. Patient outcome after RF was based on patient questionnaires administered at latest follow-up.

The mean and standard deviation were used to describe continuous variables. Frequency analyses were used for categorical variables. For categorical variables, cross-tabulations were generated, and the Fisher exact or Pearson χ^2 test was used to compare distributions. For continuous variables, *t* tests were used to investigate differences between subsets of patients classified by categorical data. Changes in radiographic measures between baseline and 1-year follow-up were evaluated with a paired *t*-test analysis, and group comparison was performed with an unpaired *t*-test analysis.

Patients were first stratified into 1 of 2 groups; those with a “symptomatic” RF and those with a RF discovered incidentally on radiographs. In a separate analysis, the patients were stratified based on whether they underwent revision after RF during a minimum of 6-month follow-up. Demographic, clinical, surgical, and radiographic parameters were compared both within and between these groups. Time to RF was calculated based on the time elapsed between surgery and definitive demonstration of RF on imaging. Statistical analyses were 2-sided, and $P < 0.05$ was considered statistically significant. Statistical analyses were performed with SPSS software (version 21; IBM Corp., Armonk, New York, USA).

RESULTS

Of the 343 patients with ASD who otherwise met inclusion criteria, 51 (14.9%) sustained a RF during the study period, of whom 44 (86.3%) had at least 6-month follow up after RF. Mean total follow

Table 1. Baseline Demographic Characteristics for 44 ASD Patients Who Sustained an RF During the Study Period

Parameter	All Patients	Revision		P Value
		No (n = 16)	Yes (n = 28)	
Mean age, years	61.2 ± 11.5	63.18 ± 9.48	60.1 ± 12.5	0.391
Female sex	28 (63.6%)	68.8%	60.7%	0.595
Mean BMI	29.6 ± 5.2	29.1 ± 6.35	29.9 ± 5.31	0.670
Mean CCI	2.11 ± 1.69	2.00 ± 1.58	2.16 ± 1.77	0.786
Smokers	0 (0.0%)	0.0%	0.0%	N/A
Previous spine surgery	27 (61.4%)	50%	67.9%	0.246

ASD, adult spinal deformity; RF, rod fracture; BMI, body mass index; CCI, Charlson Comorbidity Index; N/A, not available.

up was 37.8 months (range 24.5–66.7). The baseline demographic characteristics of the 44 patients who met the inclusion criteria are summarized in **Table 1**. Their mean age at the time of surgery was 61.2 years (SD 11.5 years), and 63.6% of patients were women. The mean BMI was 29.6 kg/m², and the mean Charlson Comorbidity Index (CCI) was 2.11 (SD 1.69). Overall, no patients were current smokers, and 27 patients (61.4%) had a history of previous spine surgery.

Radiographic parameters are shown in **Table 2**. The mean number of vertebral levels fused was 12.8 (SD 3.8). The fusion extended to the pelvis in 38 of 44 patients (86.4%). 3CO was performed in 25 cases (56.8%), with PSO performed in 22 cases, and vertebral column resection performed in 3 cases. 3CO was at the same level as the RF in 18 of 25 patients (72%). Interbody fusion was used in 26 cases of RF (59.1%) (transforaminal

lumbar interbody fusion, n = 17 [65.4%], anterior lumbar interbody fusion, n = 5 [19.2%]). RF occurred at the site of interbody fusion in 17 (65.4%) patients (most frequently L4–L5, n = 8 and L5–S1, n = 8). Rod material used was cobalt-chrome (36/44, 81.8%), stainless steel (4/44, 9.1%), and titanium alloy (4/44, 9.1%). In 20/44 (45.5%) patients, BMP-2 was used. BMP-2 was used at the interbody space alone in 2 cases (2/20, 10%), in the posterolateral gutter alone in 3 cases (3/20, 15%), and in both the interbody space and the posterolateral gutter in 15/20 cases (75%), with an average dose of 7.3 mg used at each level (range 4.2–9.0 mg).

RF occurred at an average 20.1 months after the index procedure, most commonly at L4–L5 or L5–S1. There were 23 (52.3%) unilateral fractures, most frequently at L3–L4 (n = 8, 34.8%) or L4–L5 (n = 8, 34.8%), and 21 (47.7%) bilateral RF, most frequently at L5–S1 (n = 10, 47.6%). During the visit at which RF was discovered, RFs were symptomatic in 26 of 44 (59.1%) patients and discovered incidentally on radiographs in 18 of 44 (40.9%) patients. RF was symptomatic in 13 of 21 (61.9%) of

Table 2. Comparison of Surgical Parameters for 44 Patients with ASD Who Sustained RF During the Study Period

Radiographic Parameter	All	Revision		P Value
		No (n = 16)	Yes (n = 28)	
Mean no. levels fused	12.8 ± 3.8	12.9 ± 3.5	12.7 ± 4.0	0.831
Rod material, %				
CC	81.8	81.3	82.1	0.908
SS	9.1	12.5	7.1	
TA	9.1	6.2	10.7	
Rod diameter ≥6.0 mm, %	9.1	12.5	7.1	0.55
Performance of 3CO, %	56.8	43.8	64.3	0.191
BMP-2 use, %	45.5	43.8	46.4	0.869
Interbody performed, %	59.1	56.3	60.7	0.775
BMP-2 at interbody, %	57.7	33.3	70.6	0.073

ASD, adult spinal deformity; RF, rod fracture; CC, cobalt chrome; SS, stainless steel; TA, titanium Alloy; 3CO, 3-column osteotomy; BMP-2, bone morphogenetic protein-2.

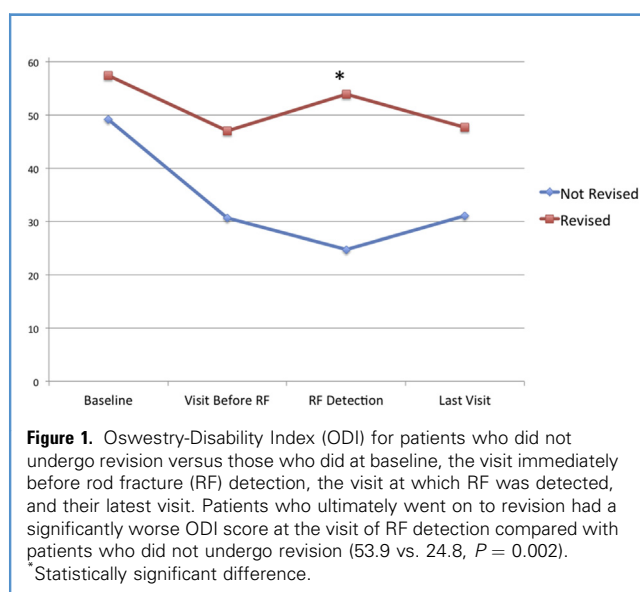


Figure 1. Oswestry-Disability Index (ODI) for patients who did not undergo revision versus those who did at baseline, the visit immediately before rod fracture (RF) detection, the visit at which RF was detected, and their latest visit. Patients who ultimately went on to revision had a significantly worse ODI score at the visit of RF detection compared with patients who did not undergo revision (53.9 vs. 24.8, $P = 0.002$). * Statistically significant difference.

patients with bilateral RF compared with 13 of 23 (56.5%) of patients with unilateral RF. BMP had been placed at the site of eventual RF in 14 of the 20 cases that used BMP during the index procedure (14/20, 70%).

During the follow-up interval, 28 RFs were revised (63.6%); 12 of 23 (52.2%) unilateral RF and 16 of 21 (76.2%) bilateral RF ($P = 0.102$). RFs were revised at an average of 2.6 months after the initial procedure (range 0.5–10.3 months). There were no differences between revised and nonrevised patients in terms of age ($P = 0.391$), sex ($P = 0.595$), mean BMI ($P = 0.670$), mean CCI ($P = 0.786$), smoking status, or previous spine surgery ($P = 0.246$). However, patients who underwent revision were significantly less likely to be female compared with patients who did not undergo revision (46.7% vs. 88.9%, $P = 0.010$). There were no other differences between patients who did or did not undergo revision in terms of rod material used, rod diameter, BMP-2 use, or interbody use (Table 2).

Patients with RF who underwent revision had a significantly worse mean ODI score (53.9, “severe disability”) compared with patients who did not undergo revision (24.8, “moderate disability”) at the visit at which RF was detected ($P = 0.002$; Figure 1). Patients with RF who underwent revision also had significantly worse SRS-22r pain score (2.48 vs. 3.47, $P = 0.018$) compared with those not revised at the visit at which RF was detected. There were no significant differences between patients who did not undergo revision for other domains of the SRS-22r, including mental health (3.70 vs. 3.862, $P = 0.656$), function (2.73 vs. 3.49, $P = 0.055$), appearance (2.97 vs. 3.49, $P = 0.121$), and satisfaction (3.89 vs. 4.23, $P = 0.406$; Figure 2). Among patients with RF who did not undergo revision, health-related quality of life (HRQoL) scores did not change over the course of mean 20.5 months (range 8.0–47.1) after RF was detected.

There was no significant difference in mean age, sex, BMI, history of previous 3CO, RF type (unilateral vs. bilateral), or use of

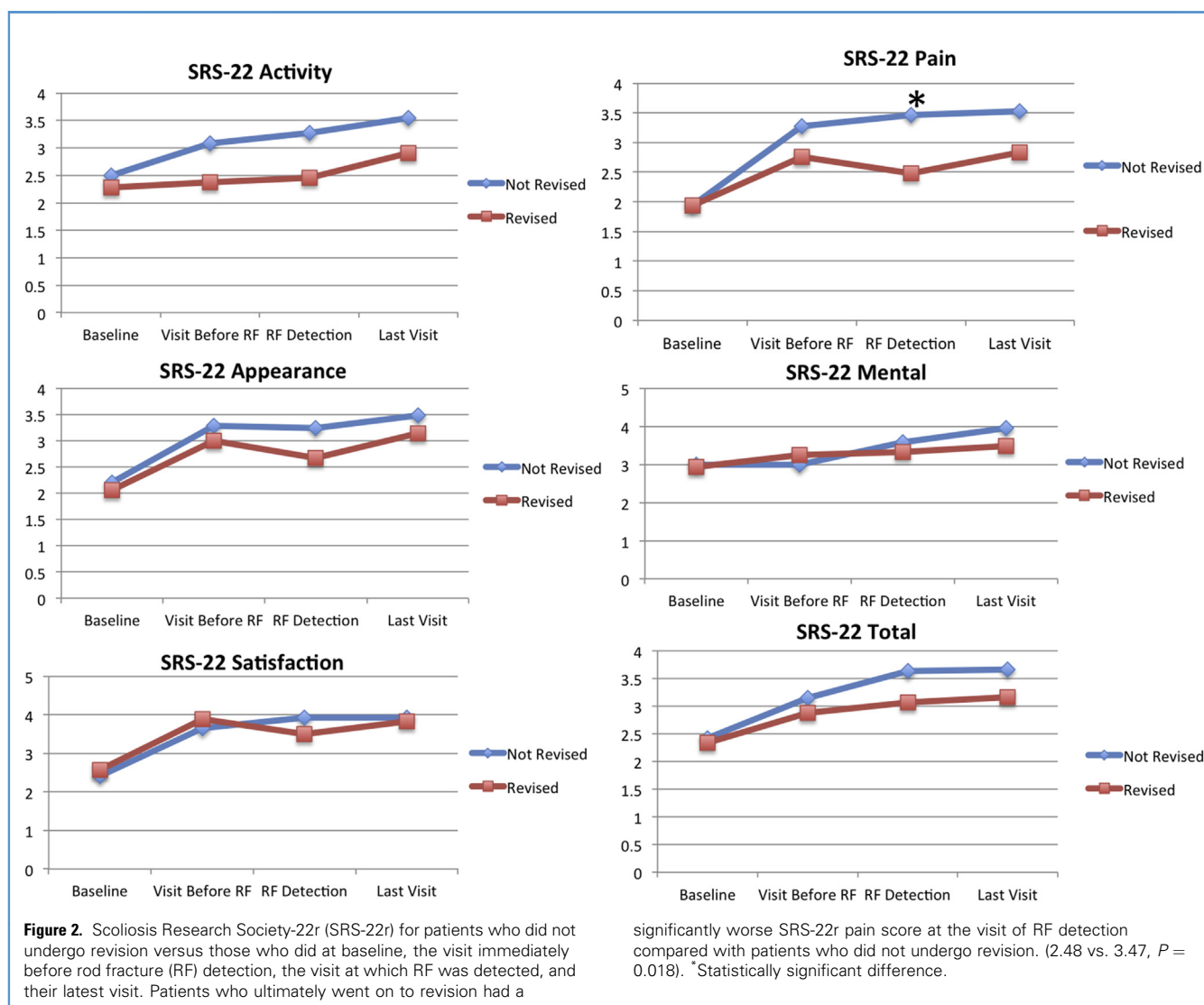


Table 3. Comparison of Baseline and Postoperative (After Primary Surgical Correction) Radiographic Measurements for 44 Patients with ASD Who Sustained a RF During the Study Period, Stratified Based on Whether the Patient Went on to Have a Revision

Radiographic Parameter	Revision		P Value
	No (n = 16)	Yes (n = 28)	
Mean max coronal Cobb angle, °			
Baseline	42.31 ± 23.02	36.10 ± 23.37	0.512
After surgical treatment	19.60 ± 18.60	18.00 ± 12.59	0.822
Change after surgery	-20.27 ± 14.88	-13.78 ± 13.37	0.295
P value	<0.001*	0.015*	—
Mean thoracic kyphosis, T4–T12, °			
Baseline	30.79 ± 18.08	22.00 ± 20.99	0.199
After surgical treatment	40.79 ± 15.91	38.79 ± 13.18	0.704
Change after surgery	10.11 ± 14.49	17.71 ± 15.32	0.1560
P value	0.007*	0.005*	—
Mean C7–S1 sagittal vertical axis, cm			
Baseline	11.11 ± 75.73	12.98 ± 91.58	0.523
After surgical treatment	3.78 ± 40.34	2.91 ± 40.20	0.543
Change after surgery	-7.01 ± 63.21	-9.00 ± 79.81	0.437
P value	<0.001*	0.004*	—
Mean pelvic tilt, °			
Baseline	25.00 ± 12.49	30.67 ± 10.32	0.171
After surgical treatment	19.89 ± 13.20	24.07 ± 6.27	0.283
Change after surgery	-4.44 ± 11.03	-5.50 ± 8.53	0.770
P value	0.085	0.039*	—
Mean pelvic incidence—lumbar lordosis mismatch, °			
Baseline	23.26 ± 23.66	36.27 ± 20.24	0.100
After surgical treatment	3.26 ± 14.74	4.79 ± 11.27	0.749
Change after surgery	-19.89 ± 20.16	-29.29 ± 20.19	0.196
P value	<0.001*	0.001*	—

ASD, adult spinal deformity; RF, rod fracture.
*Statistically significant difference.

interbody between symptomatic and asymptomatic RF. Symptomatic fractures were found to have significantly worse ODI score (51.5 vs. 25.8, $P = 0.002$), SRS-22 Pain (2.23 vs. 3.80, $P = 0.0001$), and SRS-22 Total (2.91 vs. 3.84, $P = 0.0008$) at the visit at which RF was detected. There were no significant differences between symptomatic and asymptomatic RF in SF-36 Physical ($P = 0.244$), SF-36 Mental ($P = 0.259$), NRS Back ($P = 0.167$), or NRS Leg ($P = 0.953$) at the visit at which RF was detected. Symptomatic patients were significantly more likely to undergo revision compared to asymptomatic patients (84.6% vs. 33.3%, $P = 0.0006$).

Baseline and postoperative radiographic measurements for all patients stratified based on whether or not they went on to revision are shown in **Table 3**. In both groups, there was significant improvements in mean max coronal Cobb angle ($P < 0.001$),

mean thoracic kyphosis from T4 to T12 ($P < 0.007$), mean C7–S1 SVA ($P < 0.004$), and mean PI-LL mismatch ($P = 0.001$) during their initial surgery. There were no significant differences in C7–S1 SVA (2.91 vs. 3.78 cm) between revised and nonrevised cases at the time of RF detection ($P = 0.543$).

Subanalysis of Patients without Previous 3CO

Of the 44 patients with RFs during the study period, 19 (43.2%) did not have a previous 3CO and had at least 6-month follow-up after RF (mean age = 62.3 years, mean BMI = 29.12 kg/m²). Mean total follow-up was 34.8 months (range 26–47.5). Mean time to RF was 17.9 months from index surgery (7 RF [36.8%] detected at 1-year and 12 RF [63.2%] discovered 2 years post-operatively). There were 12 (63.8%) unilateral fractures, most

frequently at L4–L5 ($n = 6$, 50%) and L5–S1 ($n = 4$, 33.3%), and 7 bilateral RF, most frequently at L5–S1 ($n = 4$, 57.1%). Overall, 6 RF were revised (31.6%); 5 of 12 (41.6%) unilateral RF and 1 of 7 (14.3%) bilateral RF. HRQoL and NRS scores were similar between patients with RF who did and did not undergo revision at the time RF was identified.

DISCUSSION

This study provides a retrospective review of a prospectively collected, multicenter assessment of RF rates, as well as both outcomes and treatment related to RF. The overall rate of RF was 14.9%, which is slightly greater than the largest series reported previously.³⁰ This may be explained by the fact that with longer follow-up, more patients develop RF. In addition, RFs may be detected incidentally on follow-up radiographs. The rate of RF is slightly greater than other smaller studies, which have reported rates from 9.3% to 10.7%.^{28,29}

The current study found that the rate of revision after RF was 63.6% (28/44 patients). We included patients with RF with a minimum of 6-month follow-up after the detection. Of revision cases, 6 of 28 (21.4%) were performed after 6 months from the time of RF detection. Therefore, the true rate of revision is likely to be greater than 63.6%, as several patients with RF may be revised with longer follow-up. To our knowledge, this is the largest series to report a rate of revision after RF.

We examined both demographic characteristics and radiographic parameters to identify factors that may be associated with RF revision. The only factor that was significantly associated with revision was male sex. Otherwise, age, mean BMI, mean CCI, smoking status, previous spine surgery, and radiographic parameters were not associated with an increased risk for revision. It is important to note these are not true “risk factors” for revision surgery. The surgeon has all patient information available (such as radiographic measurements, previous surgical procedures, etc.) when making the decision to proceed with revision surgery. Therefore, these factors are interpreted by the surgeon and patient and are not independent risk factors.

To our knowledge, this is the first study to evaluate the potential impact of HRQoL scores on RF outcome and treatment. Our primary hypothesis was that worse HRQoL and pain scores would be primary determinants of the need for revision. We found that patients that eventually underwent revision surgery had greater pain and disability scores at the time of RF detection compared to those who did not undergo revision. ODI, SRS-22 pain, and SRS-22 total scores were all lower in the revision group compared with the nonrevision group at the time of RF detection. Our secondary hypothesis was that loss of deformity correction in patients with RF would be associated with a greater

rate of revision. However, there were no differences in radiographic parameters between those who underwent revision surgery and those who did not. The results of this study suggest that HRQoL and patient-reported pain and disability may be primary determinants of the need for revision and that radiographic parameters are less important in the decision to perform revision surgery.

The rate of revision among those with previous 3CO (64.3%) was greater compared with those without (43.8%), but this did not reach statistical significance ($P = 0.10$). Previous studies have reported that previous 3CO is a significant risk factor for RF. Given instability after a 3CO, it is reasonable to suspect that surgeons may be more likely to revise these patients in the setting of a RF. We therefore performed a separate subanalysis of RF patients without previous 3CO. The revision rate for patients with RF with no history of 3CO was 43.8%. For patients with RF with no history of 3CO, HRQoL scores were again similar between revision and nonrevision cases at all time points.

This study has several potential limitations. Bone density information was not collected for each patient and was therefore not included in the study. We do not know the exact time point of fracture, so it is possible that patient-reported pain scores or radiographic parameters might have changed between the time of fracture and RF detection. We did not routinely assess fusion status based on computed tomography imaging for these patients. Therefore, we do not necessarily know whether RF was due to instrumentation failure, the development of pseudarthrosis, or some combination of these factors. As stated previously, we included RF patients with a minimum of 6-month follow-up after the occurrence. It is possible that several patients included in the nonrevised group will eventually undergo revision with further follow-up. Although we evaluated factors related to revision surgery, we did not examine the potential impact of patient or surgeon preferences on the rate of revision.

CONCLUSIONS

RFs in patients with ASD are detected between 1 and 2 years postoperatively and are most common at the L4–L5 and L5–S1 levels. Approximately two thirds (63.6%) of patients underwent revision fusion surgery in our series. There were no significant differences in the index surgery or postoperative radiographic parameters between patients who underwent revision surgery versus those treated conservatively after RF. There was a significantly greater rate of revision among patients with symptomatic RF and those with greater perceived disability and pain scores. Patient pain, disability, and symptomatology after RF may be the most important factors in the decision to perform revision surgery.

REFERENCES

1. Soroceanu A, Diebo BG, Burton D, Smith J, Deviren V, Shaffrey C, et al. Radiographical and implant-related complications in adult spinal deformity surgery: incidence, patient risk factors, and impact on health-related quality of life. *Spine*. 2015;40:1414-1421.
2. Smith JS, Shaffrey CI, Glassman SD, Carreon L L, Schwab F, Lafage V, et al. Clinical and radiographic parameters that distinguish between the best and worst outcomes of scoliosis surgery for adults. *Eur Spine J*. 2013;22:402-410.
3. Bridwell KH, Baldus C, Berven S, Edwards C, Glassman S, Hamill C, et al. Changes in radiographic and clinical outcomes with primary treatment adult spinal deformity surgeries from two years to three- to five-years follow-up. *Spine*. 2010;35:1849-1854.
4. Smith JS, Lafage V, Shaffrey CI, Schwab F, Lafage R, Hostin R, et al. Outcomes of operative and nonoperative treatment for adult spinal deformity: a prospective, multicenter, propensity-matched cohort

- assessment with minimum 2-year follow-up. *Neurosurgery*. 2016;78:851-861.
5. Smith JS, Klineberg E, Lafage V, Shaffrey C, Schwab F, Lafage R, et al. Prospective multicenter assessment of perioperative and minimum 2-year postoperative complication rates associated with adult spinal deformity surgery. *J Neurosurg Spine*. 2016;25:1-14.
 6. Albers HW, Hresko MT, Carlson J, Hall JE. Comparison of single- and dual-rod techniques for posterior spinal instrumentation in the treatment of adolescent idiopathic scoliosis. *Spine*. 2000;25:1944-1949.
 7. Bagchi K, Mohaideen A, Thomson JD, Foley LC. Hardware complications in scoliosis surgery. *Pediatr Radiol*. 2002;32:465-475.
 8. DeWald CJ, Stanley T. Instrumentation-related complications of multilevel fusions for adult spinal deformity patients over age 65: surgical considerations and treatment options in patients with poor bone quality. *Spine*. 2006;31(19 suppl):S144-S151.
 9. Dick JC, Bourgeault CA. Notch sensitivity of titanium alloy, commercially pure titanium, and stainless steel spinal implants. *Spine*. 2001;26:1668-1672.
 10. Glassman SD, Bazzi J, Puno RM, Dimar JR. The durability of small-diameter rods in lumbar spinal fusion. *J Spinal Disord*. 2000;13:165-167.
 11. Maher T, Ottaviano D, Lapman P, Goldfarb B, Merola A, Valdevit A. A comparison of stainless steel and CP titanium rods for the anterior instrumentation of scoliosis. *Biomed Mater Eng*. 2004;14:71-77.
 12. Lindsey C, Deviren V, Xu Z, Yeh RF, Puntlitz CM. The effects of rod contouring on spinal construct fatigue strength. *Spine*. 2006;31:1680-1687.
 13. McLain RF, Burkus JK, Benson DR. Segmental instrumentation for thoracic and thoracolumbar fractures: prospective analysis of construct survival and five-year follow-up. *Spine J*. 2001;11:310-323.
 14. Nguyen TQ, Buckley JM, Ames C, Deviren V. The fatigue life of contoured cobalt chrome posterior spinal fusion rods. *Proc Inst Mech Eng H*. 2011;225:194-198.
 15. Stambough JL, El Khatib F, Genaidy AM, Huston RL. Strength and fatigue resistance of thoracolumbar spine implants: an experimental study of selected clinical devices. *J Spinal Disord*. 1999;12:410-414.
 16. Stambough JL, Genaidy AM, Huston RL, Serhan H, El-khatib F, Sabri EH. Biomechanical assessment of titanium and stainless steel posterior spinal constructs: effects of absolute/relative loading and frequency on fatigue life and determination of failure modes. *J Spinal Disord*. 1997;10:473-481.
 17. Tang JA, Leasure JM, Smith JS, Buckley JM, Kondrashov D, Ames CP. Effect of severity of rod contour on posterior rod failure in the setting of lumbar pedicle subtraction osteotomy (PSO): a biomechanical study. *Neurosurgery*. 2013;72:276-282 [discussion: 283].
 18. Villarraga ML, Cripton PA, Teti SD, Steffey D, Krisnamuthy S, Albert T, et al. Wear and corrosion in retrieved thoracolumbar posterior internal fixation. *Spine*. 2006;31:2454-2462.
 19. Bago J, Ramirez M, Pellise F, Villanueva C. Survivorship analysis of Cotrel-Dubouset instrumentation in idiopathic scoliosis. *Eur Spine J*. 2003;12:435-439.
 20. Bridwell KH, Lewis SJ, Edwards C, Lenke L, Iffrig T, Berra A, et al. Complications and outcomes of pedicle subtraction osteotomies for fixed sagittal imbalance. *Spine*. 2003;28:2093-2101.
 21. Chang KW, Cheng CW, Chen HC, Chang KI, Chen TC. Closing-opening wedge osteotomy for the treatment of sagittal imbalance. *Spine*. 2008;33:1470-1477.
 22. Hyun SJ, Rhim SC. Clinical outcomes and complications after pedicle subtraction osteotomy for fixed sagittal imbalance patients: a long-term follow-up data. *J Korean Neurosurg Soc*. 2010;47:95-101.
 23. Kim YI, Bridwell KH, Lenke LG, Cheh G, Baldus C. Results of lumbar pedicle subtraction osteotomies for fixed sagittal imbalance: a minimum 5-year follow-up study. *Spine*. 2007;32:2189-2197.
 24. O'Shaughnessy BA, Kuklo TR, Hsieh PC, Yang BP, Koski TR, Ondra SL. Thoracic pedicle subtraction osteotomy for fixed sagittal spinal deformity. *Spine*. 2009;34:2893-2899.
 25. Smith JS, Shaffrey CI, Ames CP, Demakokos J, Fu K, Keshavarzi S, et al. Assessment of symptomatic rod fracture after posterior instrumented fusion for adult spinal deformity. *Neurosurgery*. 2012;71:862-867.
 26. Tsuchiya K, Bridwell KH, Kuklo TR, Lenke LG, Baldus C. Minimum 5-year analysis of L5-S1 fusion using sacropelvic fixation (bilateral S1 and iliac screws) for spinal deformity. *Spine*. 2006;31:303-308.
 27. Wattenbarger JM, Richards BS, Herring JA. A comparison of single-rod instrumentation with double-rod instrumentation in adolescent idiopathic scoliosis. *Spine*. 2000;25:1680-1688.
 28. Yang BP, Ondra SL, Chen LA, Jung HS, Koski TR, Salehi SA. Clinical and radiographic outcomes of thoracic and lumbar pedicle subtraction osteotomy for fixed sagittal imbalance. *J Neurosurg Spine*. 2006;5:9-17.
 29. Barton C, Noshchenko A, Patel V, Cain C, Kleck C, Burger E. Risk factors for rod fracture after posterior correction of adult spinal deformity with osteotomy: a retrospective case-series. *Scoliosis*. 2015;10:30.
 30. Smith JS, Shaffrey E, Klineberg E, Shaffrey C, Lafage V, Schwab F, et al. Prospective multicenter assessment of risk factors for rod fracture following surgery for adult spinal deformity. *J Neurosurg Spine*. 2014;21:994-1003.
 31. Champain S, Benchikh K, Nogier A, Mazel C, Guise JD, Skalli W. Validation of new clinical quantitative analysis software applicable in spine orthopaedic studies. *Eur Spine J*. 2006;15:982-991.
 32. Ames CP, Smith JS, Scheer JK, Bess S, Bederman S, Deviren V, et al. Impact of spinopelvic alignment on decision making in deformity surgery in adults: a review. *J Neurosurg Spine*. 2012;16:547-564.

Conflict of interest statement: The International Spine Study Group is funded through research grants from DePuy Synthes and individual donations. P.G. Passias: consulting: Medtronic. H.J. Kim: royalties: Zimmer Biomet; consulting: K2M, Zimmer Biomet. R.A. Hart: royalties: SeaSpine, DePuy Synthes; consulting: DePuy Synthes, Globus; speaking and/or Teaching Arrangements: DePuy Synthes, Globus. M.C. Gupta: royalties: DePuy; stock ownership: Pioneer (100 Shares); private investments: Spinal Ventures (2%); consulting: DePuy, Orthofix/Medtronic; speaking and/or teaching arrangements: DePuy; Trips/Travel: DePuy Spine.

Sciubba, Daniel M.: Consulting: Medtronic (Paid directly to institution/employer), Globus, DePuy-Synthes. C.P. Ames: royalties: Biomet Spine, Stryker; consulting: Medtronic, DePuy, Stryker. V. Deviren: royalties: NuVasive; consulting: NuVasive; research support - staff and/or materials: NuVasive (paid directly to institution/employer). A. Daniels: consulting: Stryker, Globus, DePuy; trips/travel: Medtronic, Globus; research support - staff and/or materials: Orthofix (paid directly to institution/employer). V. Virginia: stock ownership: Namaris (20%); speaking and/or teaching arrangements: DePuy Synthes, Medtronic, NuVasive. S. Bess: royalties: Pioneer; consulting: K2M, AlloSource; speaking and/or teaching arrangements: K2M; Trips/Travel: K2M. E.O. Klineberg: consulting: DePuy (paid directly to institution/employer), Stryker (Paid directly to institution/employer); speaking and/or teaching arrangements: K2M (paid directly to institution/employer), AOSpine (paid directly to institution/employer). C.I. Shaffrey: royalties: Medtronic, NuVasive, Biomet; stock ownership: NuVasive (5000 Shares); consulting: Biomet, NuVasive; speaking and/or teaching arrangements: NuVasive; trips/travel: Medtronic. J.S. Smith: royalties: Biomet; consulting: Biomet, K2M, NuVasive, Cerapedics; grants: DePuy Synthes (paid directly to institution/employer); fellowship support: AO (paid directly to institution/employer), NREF (paid directly to institution/employer). The remaining authors have no conflicts to report.

Received 8 May 2017; accepted 12 July 2017

Citation: *World Neurosurg.* (2017) 106:905-911.

<http://dx.doi.org/10.1016/j.wneu.2017.07.061>

Journal homepage: www.WORLDNEUROSURGERY.org

Available online: www.sciencedirect.com

1878-8750/\$ - see front matter © 2017 Elsevier Inc. All rights reserved.