European Spine Journal
https://doi.org/10.1007/s00586-024-08160-6

ORIGINAL ARTICLE

Costs of revision operations for distal junctional kyphosis following thoracic posterior spinal fusion for adolescent idiopathic scoliosis

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Received: 27 July 2023 / Revised: 9 December 2023 / Accepted: 22 January 2024

Abstract

Purpose To assess direct costs and risks associated with revision operations for distal junctional kyphosis/failure (DJK) following thoracic posterior spinal instrumented fusions (TPSF) for adolescent idiopathic scoliosis (AIS).

Methods Children who underwent TPSF for AIS by a single surgeon (2014–2020) were reviewed. Inclusion criteria were minimum follow-up of 2 years, thoracolumbar posterior instrumented fusion with a lower instrumented vertebra (LIV) cranial to L2. Patients who developed DJK requiring revision operations were identified and compared with those who did not develop DJK.

Results Seventy-nine children were included for analysis. Of these, 6.3% developed DJK. Average time to revision was 20.8 ± 16.2 months. Comparing index operations, children who developed DJK had significantly greater BMIs, significantly lower thoracic kyphosis postoperatively, greater post-operative lumbar Cobb angles, and significantly more LIVs cranial to the sagittal stable vertebrae (SSV), despite having statistically similar pre-operative coronal and sagittal alignment parameters and operative details compared with non-DJK patients. Revision operations for DJK, when compared with index operations, involved significantly fewer levels, longer operative times, greater blood loss, and longer hospital lengths of stay. These factors resulted in significantly greater direct costs for revision operations for DJK ($76,883 v. $46,595; $p < 0.01$).

Conclusions In this single-center experience, risk factors for development of DJK were greater BMI, lower post-operative thoracic kyphosis, and LIV cranial to SSV. As revision operations for DJK were significantly more costly than index operations, all efforts should be aimed at strategies to prevent DJK in the AIS population.

Keywords Adolescent idiopathic scoliosis · Distal junctional kyphosis · Revision surgery · Risk factors · Direct costs

Introduction

Thoracic posterior spinal instrumented fusion (TPSF) remains the gold standard for operative management of adolescent idiopathic scoliosis. While TPSF provides improvement in quality of life (primarily mental health/images domains) [1–5], it is not without complications, which include new neural deficit, chronic pain, pseudarthrosis, infection, implant failure and junctional (proximal and distal) pathology [6, 7]. The 2-year reoperation rate has been estimated to be as high as 13% [8].

Distal junctional pathology, including kyphosis (DJK) and failure (DJF), has been reported to have an incidence ranging from 0.2 to 19% following TPSF for AIS [9–14]. It can present in a variety of ways, including acute fractures of the lowest instrumented vertebrae (LIV), progressive distal disc degeneration, and/or failure of the posterior ligamentous structures. The underlying mechanism behind development of DJK/DJF is likely multifactorial, including failure to restore sagittal alignment specific to the patient, variability of pelvic incidence, selection of levels, implant rigidity, and amount of correction. These risk factors are incompletely understood and deserve additional investigation.

Revision operations often are required to address DJK/DJF [15–17]. As these operations can be quite challenging,

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Published online: 20 February 2024

a deeper dive into the risk factors and associated economic impact is warranted. The purpose of this study is to assess risk factors for the development of DJK/DJF as well as the direct costs associated with revisions for DJK/DJF following TPSF for AIS.

Methods

Patient cohort

Children (ages 11–18 years old) who underwent posterior spinal fusion for adolescent idiopathic scoliosis by a single surgeon between 2014 and 2020 were reviewed. Exclusion criteria included follow-up < 2 years, cervical instrumentation, and lower instrumented vertebra (LIV) caudal to L2.

Peri-Operative data

Patient demographics including body mass index (BMI), radiographic coronal and sagittal alignment, operative data [estimated blood loss (EBL), operative time, number of levels instrumented], and post-operative data [intensive care unit (ICU) admissions and length of stay (LOS)] were collected. All revision operations for DJK/DJF during follow-up were identified.

Cost data

Direct costs were identified from direct access to medical billing. The report was generated and validated by the hospital cost accounting team at our institution (only validated financials were used). Direct costs (not charges) included all facility costs during an inpatient encounter captured by the facilities cost accounting system. Indirect costs (including hospital administrative and facilities overhead, accounting and billing, health information management, housekeeping) were excluded. Surgeons' fees were excluded because these represent a direct cost to payers but do not represent the direct cost of providing care for a specific patient. Additionally, there is not a validated cost accounting system that allocates professional costs to the encounter level at our institution.

Statistical analysis

Patients who developed DJK/DJF requiring revision operations were compared with those who did not develop DJK/DJF. Chi-squared tests were used to compare categorical variables between non-DJK/DJF patients and DJK/DJF patients. Continuous variables between non-DJK/DJF patients and DJK/DJF patients were compared using non-paired Student's t-tests. All statistical analyses were performed in Microsoft Excel. Statistical significance was set at $p < 0.05$.

Results

Seventy-nine children were included for analysis. Demographic, radiographic, and operative details are presented in Table 1. Of the 79 patients, five (6.3%) developed DJK/DJF requiring 9 revision operations. Average time to revision was 20.8 ± 16.2 months. Incidence of revision operations for distal failures did not change over the study period. Comparison of index operations is presented in Table 1. Patients who developed DJK/DJF had statistically similar pre-operative coronal curve magnitudes (main thoracic and compensatory lumbar), pre-operative sagittal alignment (thoracic kyphosis, T10-L2 kyphosis, and lumbar lordosis), and operative details (operative time, EBL, average # levels fused) compared with non-DJK/DJF patients. By contrast, patients who developed DJK/DJF had significantly greater BMIs (26.3 *v.* 20.8), significantly lower thoracic kyphosis postoperatively (13.9 *v.* 24.6°; $p < 0.01$), greater post-operative lumbar Cobb angles (19.8 *v.* 11.8°; $p = 0.02$), and significantly more LIVs cranial to the sagittal stable vertebra (SSV) (60.0% vs. 9.5%, $p = 0.01$).

Revision operations (n = 9) for DJK/DJF, when compared with index operations, involved significantly fewer # of levels fused (4.6 v. 11.5; p < 0.01), longer operative times (507 *v.* 413 min; $p < 0.01$), greater EBL (485 *v.* 246 mL; $p < 0.01$), and longer hospital lengths of stay (4.2 *v.* 6.6 days; $p < 0.01$) (Table 2). These characteristics resulted in significantly greater costs for anesthesia ($1,543 *v.* $1,047; $p < 0.01$), blood transfusions ($961 *v.* $683; $p < 0.01$), pharmacy ($19,224 *v.* 13,928; $p = 0.01$), implants ($1,268 *v.* $514), labs ($24,280 *v.* $13,564; $p < 0.01$), OR services ($1,824 *v.* $1,450; p < 0.01), recovery room ($2,323 *v.* $929; $p < 0.01$), radiology ($2,000 *v.* $1,169; $p = 0.01$), room and board ($16,663 v. $8,723; $p < 0.01$), and supplies ($8,523 *v.* $3,255; $p < 0.01$) (Table 2). In turn, the total average direct costs were significantly greater for revision operations for DJK/DJF than for index operations ($76,883 *v.* $46,595; $p < 0.01$). Total direct costs for DJK/DJF revisions amounted to 14.6% of the total direct costs of all index operations.

Times to revisions varied, with the soonest revision occurring 2 days and the longest occurring 45 months after operation (Table 3). Indications for revisions included distal junctional nonunion with implant failure (broken screw), progressive distal junctional kyphosis, and 3-column fractures of the LIV (Fig. 1). All initial revision operations involved extension of the prior posterior instrumented fusion from the thoracolumbar junction (*i.e.,* T12/L1) to the mid lumbar spine (*i.e.,* L3 or L4), and most commonly included anterior column support either

Table 1 Comparison of index operations between children without subsequent DJK and children with subsequent DJK requiring revision operation

	All Patients ($n=79$)	Non-DJK ($n=74$)	DJK ($n=5$)	p
Age	14.2 ± 2.2 (11–18)	14.2 ± 2.2 (11–18)	14 ± 2.5 (11–18)	0.44
BMI	21.2 ± 4.1 (14–31)	20.8 ± 4.0 (14–31)	26.3 ± 3.0 (21–29)	**< 0.01**
Levels Fused	11.5 ± 0.8 (9–13)	11.5 ± 0.8 (9–13)	11.4 ± 0.9 (10–12)	0.44
OR time (mins)	413 ± 67 (298–770)	412 ± 67 (298–770)	406 ± 78 (329–530)	0.42
EBL (cc)	246 ± 190 (50–1000)	236 ± 170 (50–900)	380 ± 370 (100–1000)	0.05
Main Thoracic Cobb				
Pre-Op	58.2 ± 10.4 (34–83)	58 ± 10.5 (34–83)	61 ± 8.5 (54–75)	0.26
Post-Op	5.6 ± 5.1 (0–24)	5.5 ± 5.1 (0–24)	8.4 ± 5.1 (2–15)	0.11
Lumbar Cobb (deg)				
Pre-Op	39.2 ± 8.0 (24–57)	38.8 ± 8.1 (24–57)	44 ± 4.5 (39–50)	0.11
Post-Op	12.3 ± 8.5 (0–32)	11.8 ± 8.3 (0–32)	19.8 ± 8.2 (11–28)	**0.02**
Thoracic Kyphosis				
Pre-Op	21.4 ± 13.6 (1–50)	26.6 ± 8.0 (18–39)	21.0 ± 13.9 (1–50)	0.19
Post-Op	14.5 ± 8.1 (1–39)	24.6 ± 7.4 (13–31)	13.9 ± 7.7 (1–39)	**< 0.01**
T10-L2 Kyphosis				
Pre-Op	7.6 ± 8.7 (0–40)	8.0 ± 8.9 (0–40)	3.2 ± 4.1 (0–10)	0.12
Post-op	5.5 ± 4.8 (0–19)	5.4 ± 4.7 (0–19)	7.4 ± 7.0 (1–15)	0.19
Lumbar Lordosis (deg)				
Pre-Op	56.9 ± 12.0 (30–84)	56.5 ± 12.0 (30–84)	63.4 ± 12.0 (46–74)	0.11
Post-Op		46.2 ± 14.3 (8–77)	49 ± 18.5 (20–67)	0.34
LIV relative to SSV				
Cranial	10 (12.6%)	7 (9.5%)	3 (60.0%)	**0.01**
At	13 (16.5%)	13 (17.6%)	0 (0%)	0.58
Caudal	56 (70.9%)	54 (72.9%)	2 (40.0%)	0.14
LOS (days)	4.2 ± 1.1 (3–8)	4.2 ± 1.1 (3–8)	3.6 ± 0.5 (3–4)	0.11
Direct Costs (Total)	46,595 ± 6,109 (33,043–66,081)	46,700 ± 6,162 (33,043–66,081)	45,033 ± 5,626 (40,660–54,888)	0.28
Direct costs (Subcategories)				
Anesthesia	1047 ± 389	1,048 ± 400	1026 ± 196	0.45
Blood	257 ± 334	129 ± 270	18 ± 39	0.18
Pharmacy	683 ± 247	692 ± 251	552 ± 134	0.11
Implants	13,928 ± 2,420	13,879 ± 2,491	14,656 ± 2,755	0.25
Labs	514 ± 225	525 ± 225	354 ± 179	0.05
OR Services	13,564 ± 3,567	13,700 ± 3,628	11,544 ± 1579	0.10
Other	1450 ± 274	1452 ± 282	1415 ± 120	0.38
PACU	1382 ± 1,050	1386 ± 1,060	1,322 ± 1013	0.45
PT/OT	929 ± 266	922 ± 271	1,037 ± 161	0.18
Radiology	1169 ± 642	1163 ± 644	1247 ± 671	0.39
Room/Board	8723 ± 2,972	8788 ± 3,038	7759 ± 1589	0.23
Supplies	3255 ± 2,522	3197 ± 2,439	4111 ± 3801	0.22

Bold indicates statistical significance of $p < 0.05$

through an anterior approach or posterior approach (*i.e.,* TLIF) (Table 3) to provide additional stability and achieve fusion at the LIV. One patient required extension to the pelvis for recurrent distal junctional failures (Table 3, Fig. 1).

Discussion

Distal junctional kyphosis and failure following thoracic posterior spinal instrumented fusions for adolescent idiopathic scoliosis is an incompletely understood phenomenon that often requires revision operation, which is costly. In this

Table 2 Comparison of Index operations to Revision operations for DJK/DJF

	All Patients (n = 79)	DJK (n = 5 pts; 9 operations)	p
Age	14.2 ± 2.2 (11–18)	15.7 ± 2.6 (12–20)	**0.04**
Levels Fused			
Anterior	0	1.86 ± 1.6 (0–4)	n/a
Posterior	11.5 ± 0.8 (9–13)	4.6 ± 1.3 (3–6)	**< 0.01**
OR time (mins)	413 ± 67 (298–770)	474 ± 124 (284–675)	**< 0.01**
EBL (cc)	246 ± 190 (50–1000)	489 ± 256 (100–1000)	**< 0.01**
LOS (days)	4.2 ± 1.1 (3–8)	6.6 ± 7.3 (3–23)	**< 0.01**
Direct Costs (Total)	46,595 ± 6,109 (33,043—66,081)	76,883 ± 55,036 (42,662—199,796)	**< 0.01**
Direct Costs (Sum)	3,680,970	538,180	
Direct costs (subcategories)			
Anesthesia	1,047 ± 389	1,543 ± 822	**< 0.01**
Blood	122 ± 262	474 ± 361	0.13
Pharmacy	683 ± 247	961 ± 617	**0.01**
Implants	13,928 ± 2,420	19,224 ± 12,843	**< 0.01**
Labs	514 ± 225	1,268 ± 1,613	**< 0.01**
OR Services	13,564 ± 3,567	24,280 ± 15,830	**< 0.01**
Other	1,450 ± 274	1,824 ± 1,029	**0.01**
PACU	1,382 ± 1,050	1,630 ± 708	0.32
PT/OT	929 ± 266	2,323 ± 3,375	**< 0.01**
Radiology	1,169 ± 642	2,000 ± 1,929	**0.01**
Room/Board	8,723 ± 2,972	16,663 ± 17,050	**< 0.01**
Supplies	3,255 ± 2,522	8,523 ± 9,704	**< 0.01**

Bold indicates statistical significance of $p < 0.05$

cohort analysis at a single center, we assessed risk factors for the development of DJK/DJF as well as the costs associated with revisions for DJK/DJF following TPSF for AIS. There were three major findings, which may be divided into patient and curve characteristics, surgical intensity, and cost. First, risk factors for the development of DJK/DJF included greater BMI, lower post-operative thoracic kyphosis, greater post-operative lumbar Cobb angles, and LIV cranial to the SSV were risk factors for DJK/DJF revision. Second, revision operations for DJK/DJF were longer than the index procedure, had more blood loss, and required longer lengths of stay. Third, revision operations for DJK/DJF were associated with significantly greater direct costs ($76,883 *v.* $45,033 for index procedure), which accounted for 14.6% of all total direct costs of all index operations. The results regarding the risk factors for DJK/DJF found in this study are in concordance with prior reports. Our cost data are the first on this topic in the literature.

The prevalence of DJK/DJF in our cohort was 6.3%, which is in-line with the reported incidence of 0.2–19% in the literature for AIS patients [9–14]. Risk factors for DJK/DJF identified in this study were related to choice of the LIV (cranial to the SSV), greater BMI, and lack of restoration of thoracic kyphosis, which are in concordance with prior reports [10–12, 18, 19]. The concept of the sagittal stable vertebrae (SSV) is in flux. Originally, SSV was defined in Scheuermann kyphosis as the LIV being touched by a line drawn vertically from the posterior superior corner of the sacrum on the lateral radiograph, akin to selection of LIV on the coronal plane image [20]. Such is the risk of DJK/DJF that there is a current movement toward requiring the SSV to be bisected by the vertical sagittal line. The rate of DJK/DJF following TPIF is significantly higher when the LIV is cranial to the SSV (17%) compared with when the LIV included the SSV or was inferior to SSV (0%) [13]. Additionally, DJK/DJF rates increased as the LIV was further from the SSV (LIV 1-, 2-, and 3-levels above SSV were 17%, 7%, and 43%, respectively) [13]. In a separate study of 856 patients, incidence of DJK/DJF was 7.7% for patients with a LIV including the SSV compared with a DJK/DJF incidence of 45.5% for patients with a LIV short of the SSV [12]. Furthermore, it was reported that patients with Lenke Modifier type B and C had a 9.2 times increased risk of developing DJK/DJF at 2 years if LIV was short of the SSV compared with when LIV included the SSV [12]. The predictive value of LIV relative to SSV for the development of DJK/DJF continues to 5 years after operation (DJK/DJF rates: 2.2% for LIV distal to the SSV; 6.5% for LIV at the SSV; 15% for LIV cranial to SSV) [18].

Table 3 Operative details and direct costs for each DJK/DJF revision operation by patient

#	Index	Revision	Age at revision	Time to revision (mos)	OR time (mins)	EBL (cc)	LOS (days)	Total direct costs ($)—revision	Total direct costs ($)—index
1	T3-L1 PSF	PSF Extension to L3 w/ T11-L3 ASF	15	17.1	675	500	5	67,810	42,496
		L2-3 & L3-4 DLIF w/PSF extension to L4	15	3.1	435	500			
		PSF extension to pelvis w/ L2-4 lami	15	2 days	433	1000	23	199,796	
		L4-S1 ALIF	15		284	500			
2	T2-L1 PSF	PSF extension to L3 w/ L1-2 TLIF	20	25.4	424	100	3	49,133	42,979
3	T1-L1 PSF	PSF extension to L4 w/ T11-L3 ASF	12	9.6	661	300	3	68,638	54,888
		L3-4 DLIF & L2-4 PSF revision	15	38.2	478	800	4	51,647	
4	T3-12 PSF	PSF extension to L3	15	7	340	400	5	42,662	40,660
5	T2-L1 PSF	PSF extension to L3 w/T12-L1 TLIF	18	45.3	535	300	3	58,495	43,691
AVG			15.7 ± 2.6	20.8 ± 16.2	474 ± 124	489 ± 256	6.6 ± 7.3	76,883 ± 55,036	45,033 ± 5,626

DLIF = direct lateral interbody fusion

In addition to the relationship of LIV to SSV, we found that greater BMI and lack of restoration of thoracic kyphosis were risk factors for DJK. While the exact mechanism is not clear, these findings suggest that inadequate restoration of sagittal alignment [19, 21] combined with increased loads from larger body habitus create an unfavorable biomechanical environment at the distal junction (likely increased cantilever forces), which results in adjacent segment disc degeneration, pseudarthrosis, vertebral body fracture, vertebral body subluxation/dislocation, and/or implant failure. One important mechanism of failure in our series was a non-traumatic Chance fracture (Fig. 1), as it carries a risk of neural injury [15–17]. This first was reported in a 44-year-old man with athetoid cerebral palsy who developed a non-traumatic Chance fracture at the caudal end of the segmental instrumentation [15]. Subsequent studies have highlighted its associated hazards in children and adults. In a multi-center review of 15 pediatric patients who developed DJK/DJF, 73.3% were noted to have a 3-column fracture [16]. Two of these patients developed a severe distal neural deficit, which improved incompletely after revision operation [16]. This has been reported in two adult patients, who developed a distal Chance fracture and incomplete neural deficit within 1 month after index TPIF [17]. Our patient (Table 1, patient #1) developed this type of fracture thrice: once at L1 17 months after her index T3-L1 operation, second at L3 three months after revision extension to L3, and third at L4 after the second revision to L4 (Fig. 1). Her risk factors for DJK/DJF were index LIV + 1 cranial to SSV, post-operative thoracic hypokyphosis (14°) and obesity (BMI = 32 kg/m^2) (Fig. 1).

Revision operations for DJK/DJF tend to be heterogeneous [22]. All revision operations in our study involved extension of the prior posterior instrumented fusion from the thoracolumbar junction to the mid lumbar spine (L3 or L4), and most commonly included anterior column support either through an anterior approach (ALIF vs. DLIF) or posterior approach (TLIF) to provide additional stability and to achieve fusion at the distal surgical bed. Despite fewer number of levels fused compared with index operations, revision operations were more invasive, as measured by longer operating times, greater blood loss, and longer lengths of stay. These factors resulted in significantly greater costs for anesthesia, operating room services, blood transfusions,

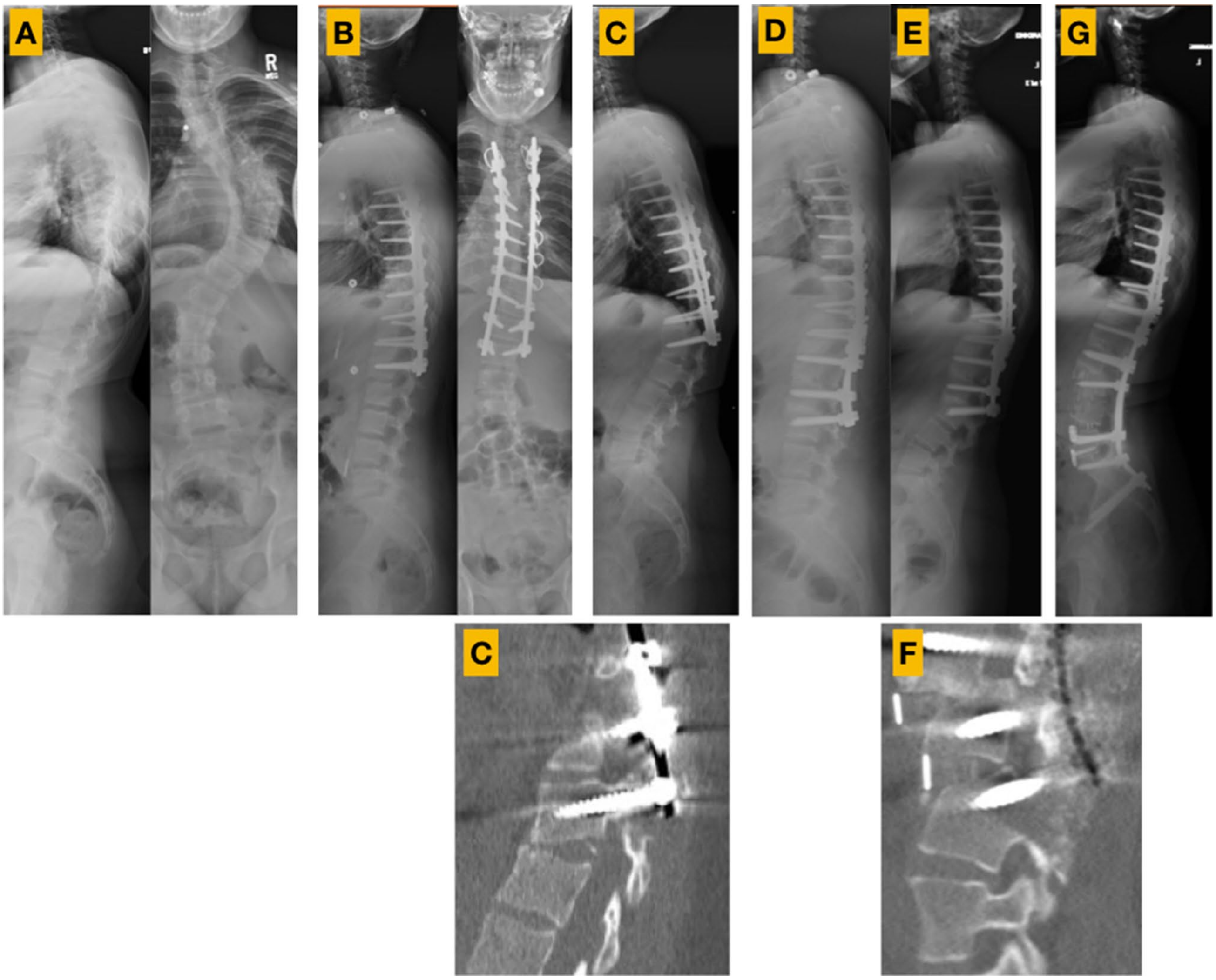

Fig. 1 A 13-year-old obese (BMI = 32 kg/m^2) girl with adolescent idiopathic scoliosis **A** underwent a T3-L1 posterior instrumented fusion **B**. Post-operative radiographs demonstrated thoracic hypokyphosis and a lower instrumented vertebrae (LIV) cranial to the pre-operative sagittal stable vertebra **B**. Seventeen months postoperatively, she developed distal junctional kyphosis and failure from a non-traumatic 3-column (Chance) fracture at the LIV **C**. An anterior spinal fusion at L1-2 and L2-3 along with an extension of the posterior instrumented fusion to L3 was then performed **D**. Three months postoperatively, she was noted to have recurrent distal junctional failure **E** that was treated with L2-3 and L3-4 direct lateral interbody fusions and posterior extension to L4. While in the hospital (on post-operative day 2), she developed new pain and weakness in the lower limbs. A CT scan demonstrated another 3-column (Chance) fracture at the LIV of L4 **F**. She underwent L2-4 decompression, extension to the pelvis, and L4-S1 anterior lumbar interbody fusion **G**. Her neural deficits resolved completely. Direct costs of all revision operations summed to $267,606

medications, implants, labs, recovery room, radiology, supplies and room and board. The total mean direct costs were significantly greater for revision operations ($76,883) than for index operations ($46,595).

While, this study is the first to assess direct costs associated with revision operations for DJK/DJF in children, the results are in concordance with prior studies evaluating costs of revision operations for proximal junctional kyphosis in adults [23–26]. Mean direct costs for managing PJK were calculated as $55,516 in a retrospective review of a single-center's experience [23]. In a separate retrospective analysis of 28 adult spinal deformity patients, mean inpatient cost were estimated as $77,432 for two revision operations for PJK [24]. In another cohort of 18 patients who underwent revision operations for PJK, mean direct cost was $119,217 [25]. Finally, mean direct cost of $55,547 for 57 revision operations for PJK were reported over a 10-year time period; in this study, total direct costs for revisions was $3.2 million, which represented an additional 12.1% of the total index surgical cost [26]. This is similar to our study in which total direct costs for DJK/DJF revisions amounted to 14.6% of the total direct costs of all index operations.

In addition to the risk factors identified for the development of DJK/DJF, other tactics may be considered to improve the biomechanics of the distal junction [22, 27]. Preoperatively, weight is a modifiable risk factor. Operative techniques include cement augmentation of the LIV, anterior interbody support at the distal construct level in high-risk patients (*e.g.,* BMI > 30), and supplemental posterior fixation such as sublaminar wiring of the LIV. As implementation of these strategies is relatively new, their utility is undefined. As such, future studies will ideally evaluate their relative efficacy in decreasing the risk of DJK/DJF in the AIS population.

The findings of this study should be considered in the context of its limitations. While this is a retrospective analysis of 5 patients with DJK/DJF requiring revision operations, our clinical findings are in concordance with prior reports on DJK/DJF in the adolescent population. Our data may not capture post-operative reoperations that may have occurred at other institutions; as a result, we may be underestimating the clinical and financial burden. Additionally, while the minimum follow-up was set at 2 years in an attempt to capture more delayed failures and associated revision operations, more revision operations may be captured with additional follow-up. However, as several of the revisions for distal junctional failure in this series occurred more acutely (before 1 year post-op), a longer minimum follow-up threshold would in-turn likely exclude these more acute failures. Despite these limitations, ours is the first analysis of the direct costs associated with revision operations for DJK/DJF in children following TPIF for AIS.

In conclusion, the rate of DJK/DJF requiring reoperation following TPSF for AIS was 6.3% in this single-center experience. Risk factors for development of DJK/DJF were greater BMI, lower post-operative thoracic kyphosis, greater post-operative lumbar Cobb angles, and LIV cranial to the SSV. Revision operations for DJK/DJF are more invasive (including longer operations and lengths of stay) and more costly ($538,000 for 7 episodes of care; 14.6% of all total direct costs of all index operations), which are stark reminders of the burden of this complication.

Author contributions All authors made substantial contributions to the conception or design of the work, the acquisition, analysis, or interpretation of data, drafted the work or revised it critically for important intellectual content, approved the version to be published, and agree to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

Funding No funding was received in support of the submitted work.

Data availability All data generated or analyzed during this study are included in this published article.

Code availability No software application or custom code were utilized.

Declarations

Conflict of interest The authors have no conflicts of interest to declare that are relevant to the content of this article.

Ethical approval Approval to conduct the submitted work was obtained by our institution's Institutional Review Board (IRB).

Consent to participate Waiver to consent to participate was provided by the IRB.

Consent for publication Waiver to consent to published was provided by the IRB.

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