

UCSF

UC San Francisco Previously Published Works

Title

Odontoid fractures above C2 to pelvis posterior instrumented fusions: a single centers 11-year experience.

Permalink

<https://escholarship.org/uc/item/1nd9x366>

Journal

Spine Deformity, 12(2)

Authors

Lim, Perry

Clark, Aaron

Deviren, Vedat

et al.

Publication Date

2024-03-01

DOI

10.1007/s43390-023-00800-z

Copyright Information

This work is made available under the terms of a Creative Commons Attribution License, available at <https://creativecommons.org/licenses/by/4.0/>

Peer reviewed



Odontoid fractures above C2 to pelvis posterior instrumented fusions: a single center's 11-year experience

Perry Lim¹ · Aaron J. Clark² · Vedat Deviren¹ · Sigurd H. Berven¹ · Shane Burch¹ · Christopher P. Ames² · Alekos A. Theologis¹

Received: 23 September 2023 / Accepted: 25 November 2023 / Published online: 29 December 2023
© The Author(s) 2023

Abstract

Purpose To define the prevalence, characteristics, and treatment approach for proximal junction failure secondary to odontoid fractures in patients with prior C2-pelvis posterior instrumented fusions (PSF).

Methods A single institution's database was queried for multi-level fusions (6+ levels), including a cervical component. Posterior instrumentation from C2-pelvis and minimum 6-month follow-up was inclusion criteria. Patients who sustained dens fractures were identified; each fracture was subdivided based on Anderson & D'Alonzo and Grauer's classifications. Comparisons between the groups were performed using Chi-square and *T* tests.

Results 80 patients (71.3% female; average age 68.1 ± 8.1 years; 45.0% osteoporosis) were included. Average follow-up was 59.8 ± 42.7 months. Six patients (7.5%) suffered an odontoid fracture post-operatively. Cause of fracture in all patients was a mechanical fall. Average time to fracture was 23 ± 23.1 months. Average follow-up after initiation of fracture management was 5.84 ± 4 years (minimum 1 year). Three patients sustained type IIA fractures one of which had a concomitant unilateral C2 pars fracture. Three patients sustained comminuted type III fractures with concomitant unilateral C2 pars fractures. Initial treatment included operative care in 2 patients, and an attempt at non-operative care in 4. Non-operative care failed in 75% of patients who ultimately required revision with proximal extension. All patients with a concomitant pars fracture had failure of non-operative care. Patients with an intact pars were more stable, but 50% required revision for pain.

Conclusions In this 11-year experience at a single institution, the prevalence of odontoid fractures above a C2-pelvis PSF was 7.5%. Fracture morphology varied, but 50% were complex, comminuted C2 body fractures with concomitant pars fractures. While nonoperative management may be suitable for type II fractures with simple patterns, more complex and unstable fractures likely benefit from upfront surgical intervention to prevent fracture displacement and neural compression. As all fractures occurred secondary to a mechanical fall, inpatient and community measures aimed to minimize risk and prevent mechanical falls would be beneficial in this high-risk group.

Keywords Adult spinal deformity · C2-pelvis · Proximal junctional fracture · Dens fracture

Introduction

Adult spinal deformity (ASD) is a highly heterogeneous disorder that can result in considerable pain and functional disability [1–3]. Surgical management for ASD has demonstrated

cost effectiveness and beneficial outcomes compared to non-operative management [1, 3–7]. The mainstay of ASD surgical management consists of multi-level posterior instrumented fusions of the thoracolumbar spine or cervicothoracic spine. Less frequently, patients may require index or revision operations that span from C2 to the pelvis. This may be indicated for severe concomitant cervicothoracic and thoracolumbar deformities, for proximal junctional failure (PJF) following prior upper thoracic–pelvis posterior instrumented fusions, or for distal junctional failures following prior cervicothoracic posterior instrumented fusions. While prior reports have demonstrated that cervical to pelvis posterior instrumented fusions can provide considerable improvement in function [8],

✉ Alekos A. Theologis
alekos.theologis@ucsf.edu

¹ Department of Orthopaedic Surgery, University of California-San Francisco (UCSF), 500 Parnassus Ave, MUW 3 Floor, San Francisco, CA 94143, USA

² Department of Neurological Surgery, UCSF, San Francisco, CA, USA

rigidity of the entire spine creates junctional stresses at C2 that increases the risk of dens fractures.

Proximal junctional failure following long thoracolumbar posterior instrumented fusions remains a vexing phenomenon that can jeopardize outcomes, result in considerable morbidity, and often necessitate revision operations [9–12]. While there is a plethora of knowledge regarding PJF following thoracolumbar fusions, there is a dearth of information regarding proximal junctional dens fractures [9–20]. As such, the aim of this study is to define the prevalence, characteristics, and treatment approach for PJF secondary to odontoid fractures in patients with prior C2–pelvis posterior instrumented fusions.

Methods

After Institutional Review Board approval, a surgical database between July 2012 and March 2023 was queried for patients who underwent multi-level posterior instrumented fusions consisting of ≥ 6 levels and including the cervical spine. Posterior segmental instrumentation from C2 to the pelvis (Fig. 1) and a minimum of 6 months of follow-up from the index operation were used as inclusion criteria. Patient demographics, including age, sex, body mass index (BMI), comorbidities, and the Charlson Comorbidity Index (CCI) [21], were recorded. Other clinical and surgical parameters included estimated blood loss (EBL), hospital length of stay (H-LOS), type of operation resulting in the C2–pelvis instrumentation (i.e., primary C2–pelvis PSF, extension of subaxial cervical–pelvis PSF to C2, extension of thoracic–pelvis PSF to C2, extension of C2–thoracic PSF to pelvis), use of a 3-column osteotomy (3CO), and post-operative complications.

Patients who sustained proximal junctional dens fractures as a complication post-operatively were identified by chart review. The diagnosis of each fracture was confirmed radiographically and verified by a fellowship-trained spinal surgeon from cervical computed tomography (CT) scans. Data regarding their clinical courses following fracture were assessed and the following were recorded: mechanism of injury, initial treatment modality (operative vs. nonoperative), date of revision operation relative to index operation, follow-up after definitive fracture management, reason for revision (i.e., pain, neurological symptoms, fracture displacement, etc.), and type of revision operation. In addition, cervical CT scans were reviewed and used to classify the type of dens fracture. Each fracture was classified based on the Anderson & D’Alonzo classification system (Type I—tip; Type II—base; Type III—body) [22]. Type II fractures’ morphology were further sub-classified based on the Grauer classification (Type A—horizontal fracture line; Type B—oblique fracture line from anterior/superior to posterior/inferior; Type C—oblique fracture line from anterior/inferior to posterior/superior—“reverse obliquity”) [23]. Fracture union was assessed with CT scans after 1 year following definitive management treatment.

Patient characteristics and revisions were compared between patients with and without a proximal junctional dens fracture. For categorical variables, χ^2 tests were used to compare distributions. For continuous variables, student *T* tests were used to investigate differences in the distribution between the fracture and non-fracture cohorts. The level of significance was set at $p < 0.05$ for all tests. All data analysis performed utilized the Analyze-it software package in conjunction with Microsoft Excel.

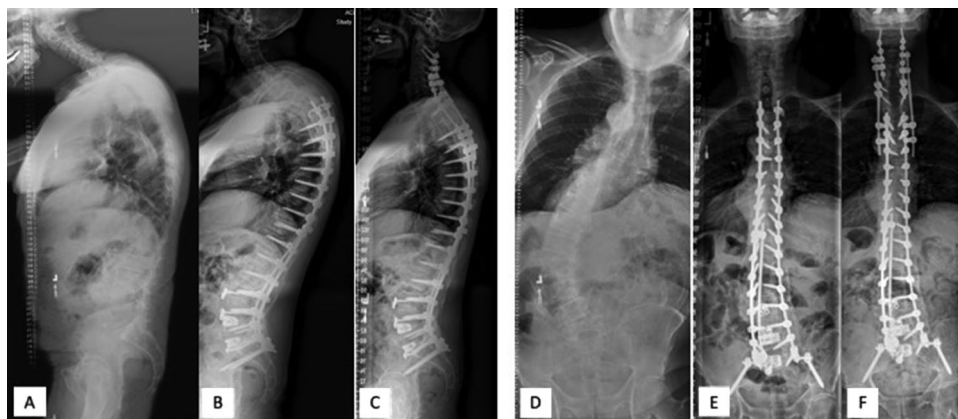


Fig. 1 Representative radiographic example of a patient who underwent C2–pelvis posterior instrumented fusion for adult spinal deformity. A 67-year-old male with concomitant thoracolumbar scoliosis and cervicothoracic kyphosis (A, D) who was treated in a staged approach. First, he underwent an L3–S1 anterior lumbar interbody

fusion and T3–pelvis posterior instrumented fusion (B, E) to address the thoracolumbar scoliosis. Three months later, an extension of posterior instrumentation to C2 with C7–T4 posterior column osteotomies was performed to address the persistent cervicothoracic deformity (C, F)

Results

Patient cohort (Table 1)

Eighty patients had C2-pelvis posterior instrumented fusions and were included for analysis. Average age was 68.1 ± 8.1 years. The majority (71.3%) were female. Average CCI was 3.7 ± 1.7 and average BMI was 28.7 ± 5.7 . Of the 80 patients, 45.0% had osteoporosis. Average EBL for index C2-pelvis PSF was $1671 \pm 1,471$ mL (300–8000 mL). While occurrence of any complication was common ($n=51$), complications were variable and each in isolation was uncommon. Neurological complications included cervical palsy (3.8%), brachial plexopathy (2.5%), epidural hematoma (2.5%), Bell's palsy (1.4%), stroke (1.3%), and cauda equina syndrome (1.3%). Pulmonary complications included aspiration (2.5%), pneumothorax (1.3%), and pulmonary embolism (2.5%). Cardiac complications included atrial fibrillation (5.0%), hypotension (3.8%), myocardial infarction (2.7%), pulseless electrical activity (2.5%), and type II heart block (1.3%). Hematologic complications included deep venous thrombosis (2.5%). Infectious complications included vertebral osteomyelitis (1.3%), urinary tract infection (3.8%), *Clostridium difficile* (2.5%), and deep wound infection (1.3%). Alimentary tract complications included dysphagia (5.0%), perforated diverticulitis (1.4%), and shock liver (1.3%). Renal complications included acute kidney injury (1.3%) and hyponatremia (1.4%). Average follow-up for all patients was 59.8 ± 42.7 months.

Dens fractures (Tables 1 and 2)

Six patients (7.5%) suffered a proximal junctional odontoid fracture post-operatively. Of the odontoid fracture cohort, the average age was 71.8 ± 9.2 years, CCI was 3.2 ± 1.5 , and BMI was 23.9 ± 4.1 . All six patients in the cohort were female with 50% having osteoporosis. Patients who sustained odontoid fractures had statistically lower BMIs compared to non-fracture patients (Table 1). There were no significant differences between the two groups in regards to age, sex, CCI, osteoporosis status, EBL, H-LOS, type of index operation, and use of 3CO ($p > 0.05$) (Table 1).

The initial C2 instrumentation for the fracture cohort consisted of four (66.6%) bilateral pars screws, one (16.6%) bilateral pedicle screw, and one (16.6%) bilateral trans-laminar screw (Table 2). Cause of fracture in all patients was a mechanical fall. Average time to fracture was 23 ± 23.1 months. Fracture morphology varied, but 50% were complex, comminuted fractures of the C2 body (type III) with concomitant pars fractures (Fig. 2). Three patients sustained type IIA fractures, and one had a concomitant unilateral C2 pars fracture (Fig. 2). Three patients sustained comminuted type III fractures with concomitant unilateral C2 pars fractures (Fig. 2).

Three patients achieved fracture union with initial management, which included a collar, proximal extension to C1, or proximal extension to the occiput (Fig. 3). The other three patients were initially treated non-operatively, but later required proximal extension to the occiput or C1 for continued pain, fracture displacement, and/or C1–2 stenosis with associated cervical myelopathy (Fig. 3). The nonoperative failures were in patients with comminuted Type III or

Table 1 Comparison of characteristics between patients with and without proximal junctional odontoid fractures

Parameter	Entire cohort (n = 80)	+ Odontoid Frx (n = 6)	No Odontoid Frx (n = 74)	p
Age (years)	68.1 ± 8.1	71.8 ± 9.2	68.0 ± 8.2	0.23
Sex				
Male	23	0	23	0.11
Female	57	6	51	
BMI	28.7 ± 5.7	23.9 ± 4.1	29.1 ± 5.6	0.03
CCI	3.7 ± 1.7	3.2 ± 1.5	3.7 ± 1.7	0.43
Osteoporosis	36 (45%)	3 (50%)	33 (45%)	0.80
Estimated blood loss (mL)	1671 ± 1471 (300–8000)	1642 ± 1058 (400–3500)	1673 ± 1505 (300–8000)	0.96
Hospital length of stay (days)	12.9 ± 11.1	10.3 ± 7.1	13.1 ± 11.3	0.57
C2-pelvis operation type				
Primary C2-pelvis	6 (7.5%)	0 (0%)	6 (8.1%)	0.22
Extend Cervical–Pelvis to C2	10 (12.5%)	1 (16.7%)	9 (12.2%)	
Extend Thoracic–Pelvis to C2	44 (55%)	2 (33.3%)	42 (56.7%)	
Extend C2–Thoracic to pelvis	20 (25%)	3 (50%)	17 (23.0%)	
3CO	45 (56.3%)	2 (33.3%)	43 (58.1%)	0.24

Bold represents statistical significance ($p < 0.05$)

Frax fracture, BMI body mass index, CCI Charlson Comorbidity Index, 3CO 3-column osteotomy

Type IIA fractures with unilateral C2 pars fractures. The 5 revision operations to address the odontoid fractures had an average EBL of 262.5 ± 188.7 mL (50–500 mL) and an average H-LOS of 5.8 ± 1.7 days. None of the revision surgeries experienced a post-operative complication. All fractures healed after surgery. Average follow-up after definitive fracture management was 5.84 ± 4 years.

Discussion

Proximal junctional failures following posterior instrumented fusions for adult spinal deformity remain challenging clinical and surgical dilemmas. An odontoid fracture cranial to a prior C2–pelvis posterior instrumented fusions represents a unique subset of PJFs that is poorly understood. In this study, we have presented for the first time the prevalence, characteristics, and treatment approaches for PJF secondary to odontoid fractures in patients with prior C2–pelvis posterior instrumented fusions at a single institution over an 11-year timeframe. There were 3 major findings to this study: (1) the prevalence of proximal junctional dens fractures was 7.5%; (2) dens fracture morphology varied, but 50% were complex, comminuted C2 body fractures (type III) with concomitant pars fractures; and (3) nonoperative management was not suitable for comminuted dens fractures with concomitant C2 pars fractures. These results

complement, expand upon, and bridge the disparate fields of spinal trauma and spinal deformity.

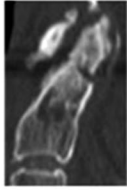

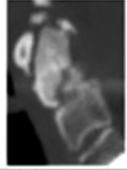
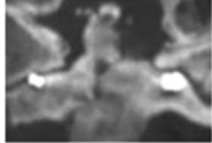
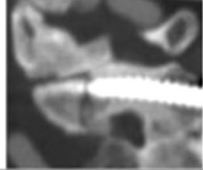
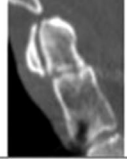

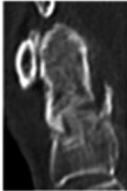
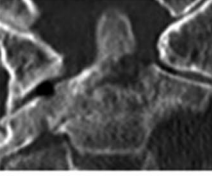
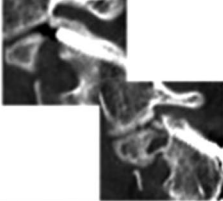

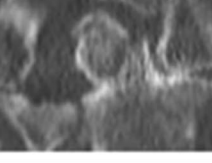


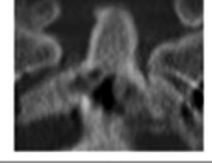
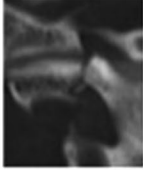
Optimal management of dens fractures is a topic of considerable interest and controversy. This is particularly so for type II dens fractures in elderly patients. While several reports support operative management given high risk of nonunion and jeopardized survival with nonoperative management [24, 25], others favor nonoperative management for elderly patients given increased mortality rates and complications with operative treatment [26]. For type III fractures, the literature appears in agreement that nonoperative management with external immobilization results in acceptable outcomes with union rates of 85–100% [27, 28]. Several of the considerations that go into treatment of isolated dens fracture in the elderly are applicable to our cohort, particularly risks of surgery in frail individuals and loss of rotation associated with immobilization of C1–2 and loss of flexion–extension with occipitocervical instrumentation. As C2–pelvis patients' only spinal motion segments are C1–2 and occiput–C1, preservation of this motion through nonoperative care of a proximal junctional dens fracture would clearly be preferred if it were safe and effective. In our cohort, four out of six patients were treated nonoperatively initially. Of these four patients, three (75%) later required proximal extension to the occiput or C1 for continued pain, fracture displacement, rigid torticollis, and/or C1–2 stenosis with associated cervical myelopathy. It is important to note that all three nonoperative failures were in patients

Table 2 Characteristics of patients who sustained proximal junctional odontoid fractures

	#1	#2	#3	#4	#5	#6
Age (years)	69	79	82	71	61	74
BMI	22.2	29	17	24	26	25
CCI	2	4	4	5	1	3
Osteoporosis	Yes	Yes	No	No	Yes	No
Initial C2 instrumentation	B/L pars screws	B/L pedicle screws	B/L pars screws	B/L pars screws	B/L pars screws	B/L translaminar screws
Time to fracture (months)	1.1	31.1	1.2	10.0	59.7	34.8
Mechanism of Frx	Fall	Fall	Fall	Fall	Fall	Fall
Frax classification						
Anderson/D'Alonzo	II	III + unilateral C2 pars frx	II	III + unilateral C2 pars frx	II + unilateral C2 pars frx	III + unilateral C2 pars frx
Grauer	A	N/A	A	N/A	A	N/A
Failure of nonop	No	Yes	No	Yes	Yes	No
Treatment	Non-op	Extension to C1	Extension to C1	Extension to occiput	Extension to occiput	Extension to occiput
Reason for revision	N/A	Pain, Frx displacement	Pain	Pain, Frx displacement	Frax, displacement; torticollis; C1–2 stenosis w/ myelopathy	Pain

Frax fracture, BMI body mass index, CCI Charlson Comorbidity Index, B/L bilateral

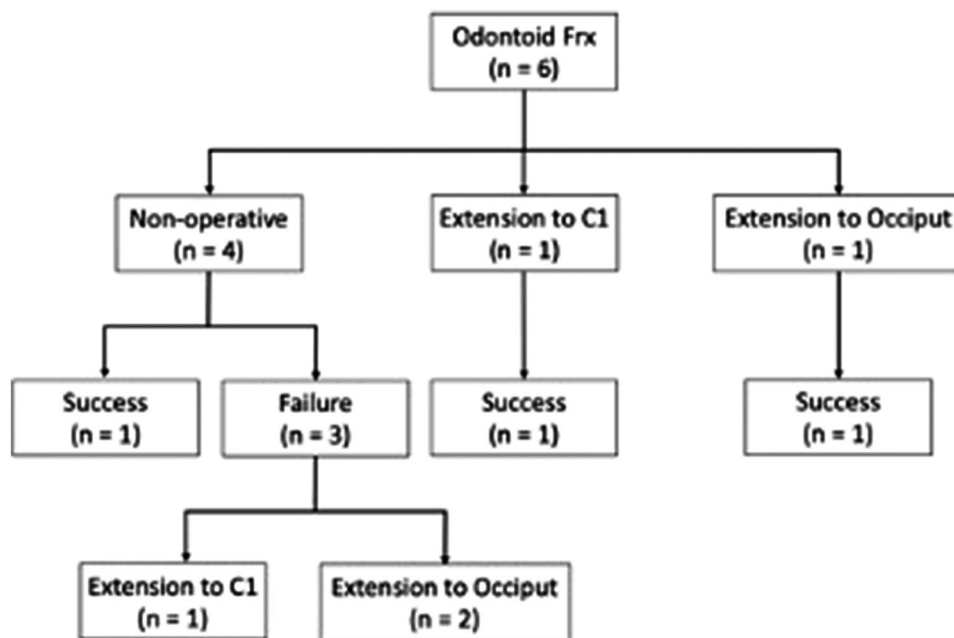
Fig. 2 Fracture characteristics and morphology of proximal junctional dens fractures for each patient

Pt	Sagittal	Coronal	Pars Fracture	Type	Trtmt
1			No	IIA	Nonop
2				III	Extension to C1 after nonop failure
3			No	IIA	Extension to C1
4				III	Extension to occiput after nonop failure
5				II	Extension to occiput after nonop failure
6				III	Extension to occiput

with comminuted Type III fractures with unilateral C2 pars fractures and the one successful outcome from nonoperative management was in a 69-year-old female who had a non-comminuted Type IIA fracture. Therefore, while non-operative management may be suitable for type II fractures with simple fracture patterns, more complex and unstable fractures likely benefit from upfront surgical intervention to prevent fracture displacement, neural compression, and post-traumatic deformities, which may be more challenging and riskier to treat than the original injury. Despite the functional limitations from loss of range of motion secondary to immobilization of C1–2 and/or occiput-C1, the clinical, surgical, and economic consequences of a less-definitive treatment should be considered.

One upfront surgical intervention that can be considered to provide immediate stability, but preserve motion in the long term is to perform a proximal extension of instrumentation for fracture stabilization without fusion followed by removal of the instrumentation once the fracture heals. This approach has been previously demonstrated feasible, safe, and effective for isolated dens fractures as well as proximal junctional dens fractures [29–31]. Temporary fixation for isolated dens fractures was first reported by Han et al. who reported on 13 patients in whom dynamic CT scans demonstrated restoration of neck rotation compared to matched historic controls following dens fracture union and removal of temporary C1–2 fixation [31, 32]. In addition to restoration of motion, Guo et al. found that patients who had removal of C1–2 temporary instrumentation for dens fractures had

Fig. 3 Schematic of management of proximal junctional odontoid fractures. “Success” of treatment is defined as fracture union as assessed by CT scan at least 1 year post-operatively



significantly less neck pain, less neck stiffness, lower disability scores, greater satisfaction, and higher general functional scores compared to odontoid fractures treated with permanent posterior instrumented C1–2 fusions [30]. In 2017, Theologis et al. presented a case report of a 74-year-old female who was treated with extension of instrumentation to the occiput (no attempt at fusion was performed) for a displaced odontoid fracture with an unilateral C2 pars fracture after a mechanical fall 3 years after a C2–pelvis posterior instrumented fusion [29]. Post-operatively, severely limited neck range of motion was highly disabling to the patient, which was reflected in worsening of health-related quality of life scores [29]. The fracture healed uneventfully after which the instrumentation from the occiput and C1 were removed, which resulted in improvement of neck range of motion as well as minimal neck disability, no neck and arm pain, and outstanding general health functional scores [29].

In addition to management considerations, a discussion on prevention of these complicated junctional fractures is warranted. Intra-operative methods to consider to prevent proximal junctional dens fractures are placement of a prophylactic anterior odontoid screw with or without cement augmentation [33–35]. While an odontoid screw may theoretically prevent dens fractures, it may not be a viable strategy for a couple reasons. First, it would require a separate surgical anterior cervical approach, which would risk dysphagia in an elderly, frail cohort. Second, that a large proportion of our cohort’s fractures were comminuted body fractures with concomitant pars fractures raises the question of whether a simple odontoid screw would be efficacious in preventing these complicated fracture patterns. Another potential preventative measure could be cement

augmentation of C2, which has been demonstrated safe and effective for treatment of cancerous lesions of the dens through minimally invasive anterior approaches (transoral and anterolateral) [36–43]. This theoretically could be performed pre-operatively, intra-operatively, or post-operatively in a staged fashion. These thoughts should neither be considered a recommendation nor advocacy for these techniques, but instead offer potential avenues to consider exploring in the future. Conversely, we favor promoting measures aimed to minimize risk of mechanical falls given that all our patients’ fractures occurred secondary to a mechanical fall [44]. A systematic review found that the following guidelines were strongly recommended to minimize falls: risk stratification, assessment tests for gait and balance, fracture and osteoporosis management, medication review, exercise promotion, environment modification, vision and footwear correction, referral to physiotherapy, and cardiovascular interventions [44].

The results of this study should be considered in the context of its limitations. The major limitations all stem primarily from the infrequent occurrence of patients being instrumented from C2 to the pelvis. Despite being an extremely high-volume adult spinal deformity center, only 80 patients with C2–pelvis posterior instrumentation constructs over an 11-year timeframe were performed (< 8 cases per year). As such, the resultant patient cohort of interest (i.e., proximal junctional dens fracture) was quite small and had considerable heterogeneity with regards to medical and surgical profiles and follow-up duration. In turn, our findings may not be generalizable and/or representative of the experience of the spine community as a whole. Furthermore, evolving practice patterns and inconsistent utilization of patient reported

outcome measures over the 11-year study period rendered inclusion of validated clinical outcome measures not possible. In addition, while all patients received treatment for osteoporosis peri-operatively, the treatment approaches (i.e., duration of treatment, type of pharmacology, assessment of treatment “efficacy”) were quite variable given changing practice patterns. In addition to osteoporosis management, it is possible that other factors may have been involved in the development of the fractures, including, but not limited to, post-operative radiographic alignment parameters. However, given that all the fractures in our cohort occurred following mechanical falls, radiographic alignment parameters likely play a negligible role in the development of these types of adjacent fractures, and thus, their measurement was felt to be outside the scope of this study. While our minimum follow-up of 6 months may be considered incomplete, it encompasses all patients who may have developed acute PJF, as defined by the development of PJF within 6 months after operation [13, 45]. Furthermore, given that the vast majority of patients who present to other hospitals are commonly transferred back to our hospital for management given complexity of their previous spine surgeries, patients included in this study are likely a good representation of the prevalence of dens fractures in this unique patient cohort. Despite these limitations, this is the most robust cohort to be presented on patients who had prior C2-pelvis posterior instrumented fusions and the first study on proximal junctional dens fractures. As such, we anticipate that our observational findings will bring awareness to this challenging problem and will ideally be a launching pad from which multi-center retrospective and prospective investigations will be initiated to assist in fully appreciating the incidence, burden of disease, and optimal methods to prevent and treat this unique subset of PJF.

Conclusions

In this 11-year experience at a single institution, the prevalence of odontoid fractures above a C2-pelvis PSF was 7.5%. Fracture morphology varied, but 50% were complex, comminuted C2 body fractures (type III) with concomitant pars fractures. While nonoperative management may be suitable for type II fractures with simple patterns, more complex and unstable fractures likely benefit from up front surgical intervention to prevent fracture displacement and neural compression. These results highlight the need for surgeons to be cognizant of the risk of odontoid fractures after C2-pelvis posterior instrumented fusions and provide some guidance on how to approach initial management. Importantly, as all fractures occurred secondary to a mechanical fall, inpatient and community measures aimed to minimize risk and

prevent mechanical falls would be beneficial in this high-risk group. Additional clinical investigations, including multi-center data, will be helpful to fully appreciate the incidence, burden of disease, and optimal methods to prevent and treat this unique subset of PJF.

Author contributions Made substantial contributions to the conception or design of the work; or the acquisition, analysis, or interpretation of data; or the creation of new software used in the work: PL, AJC, SHB, SB, CPA, AAT. Drafted the work or revised it critically for important intellectual content: PL, AJC, SHB, SB, CPA, AAT. Approved the version to be published: PL, AJC, SHB, SB, CPA, AAT. 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: PL, AJC, SHB, SB, CPA, AAT.

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

Data availability The data that support the findings of this study are available from the corresponding author, AAT, upon reasonable request.

Declarations

Conflict of interest None relevant to the submitted work.

IRB approval Obtained.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article’s Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article’s Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

1. Smith JS, Line B, Bess S et al (2017) The health impact of adult cervical deformity in patients presenting for surgical treatment: comparison to United States population norms and chronic disease states based on the EuroQol-5 Dimensions Questionnaire. *Neurosurgery* 80:716–725
2. Passias PG, Poorman GW, Lafage V et al (2018) Cervical versus thoracolumbar spinal deformities: a comparison of baseline quality-of-life burden. *Clin Spine Surg* 31:413–419
3. Durand WM, Babu JM, Hamilton DK et al (2022) Adult spinal deformity surgery is associated with increased productivity and decreased absenteeism from work and school. *Spine* 47:287–294
4. Paulus MC, Kalantar SB, Radcliff K (2014) Cost and value of spinal deformity surgery. *Spine* 39:388–393
5. Smith JS, Kelly MP, Yanik EL et al (2021) Operative versus non-operative treatment for adult symptomatic lumbar scoliosis at 5-year follow-up: durability of outcomes and impact of treatment-related serious adverse events. *J Neurosurg Spine* 35:67–79

6. Smith JS, Shaffrey CI, Berven S et al (2009) Operative versus nonoperative treatment of leg pain in adults with scoliosis: a retrospective review of a prospective multicenter database with two-year follow-up. *Spine* 34:1693–1698
7. Bridwell KH, Glassman S, Horton W et al (2009) Does treatment (nonoperative and operative) improve the two-year quality of life in patients with adult symptomatic lumbar scoliosis: a prospective multicenter evidence-based medicine study. *Spine* 34:2171–2178
8. Iyer S, Kim HJ, Theologis A et al (2019) Outcomes of fusions from the cervical spine to the pelvis. *Glob Spine J* 9:6–13
9. Yagi M, King AB, Boachie-Adjei O (2012) Incidence, risk factors, and natural course of proximal junctional kyphosis: surgical outcomes review of adult idiopathic scoliosis. Minimum 5 years of follow-up. *Spine* 37:1479–1489
10. Kim YJ, Bridwell KH, Lenke LG et al (2008) Proximal junctional kyphosis in adult spinal deformity after segmental posterior spinal instrumentation and fusion: minimum five-year follow-up. *Spine* 33:2179–2184
11. Hart RA, Prendergast MA, Roberts WG et al (2008) Proximal junctional acute collapse cranial to multi-level lumbar fusion: a cost analysis of prophylactic vertebral augmentation. *Spine J Off J N Am Spine Soc* 8:875–881
12. Yagi M, Rahm M, Gaines R et al (2014) Characterization and surgical outcomes of proximal junctional failure in surgically treated patients with adult spinal deformity. *Spine* 39:E607–614
13. Hart R, McCarthy I, O'Brien M et al (2013) Identification of decision criteria for revision surgery among patients with proximal junctional failure after surgical treatment of spinal deformity. *Spine* 38:E1223–1227
14. DeWald CJ, Stanley T (2006) 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* 31:S144–151
15. Hart RA, McCarthy I, Ames CP et al (2013) Proximal junctional kyphosis and proximal junctional failure. *Neurosurg Clin N Am* 24:213–218
16. Hostin R, McCarthy I, O'Brien M et al (2013) Incidence, mode, and location of acute proximal junctional failures after surgical treatment of adult spinal deformity. *Spine* 38:1008–1015. <https://doi.org/10.1097/BRS.0b013e318271319c>
17. Theologis AA, Tabaraee E, Funao H et al (2015) Three-column osteotomies of the lower cervical and upper thoracic spine: comparison of early outcomes, radiographic parameters, and peri-operative complications in 48 patients. *Eur Spine J* 24(Suppl 1):S23–30
18. Lewis SJ, Abbas H, Chua S et al (2012) Upper instrumented vertebral fractures in long lumbar fusions: what are the associated risk factors? *Spine* 37:1407–1414
19. Watanabe K, Lenke LG, Bridwell KH et al (2010) Proximal junctional vertebral fracture in adults after spinal deformity surgery using pedicle screw constructs: analysis of morphological features. *Spine* 35:138–145. <https://doi.org/10.1097/BRS.0b013e3181c8f35d>
20. Jang HJ, Park JY, Kuh SU et al (2021) The fate of proximal junctional vertebral fractures after long-segment spinal fixation: are there predictable radiologic characteristics for revision surgery? *J Korean Neurosurg Soc* 64:437–446
21. Charlson ME, Pompei P, Ales KL, MacKenzie CR (1987) A new method of classifying prognostic comorbidity in longitudinal studies: development and validation. *J Chronic Dis* 40:373–383
22. Anderson LD, D'Alonzo RT (2004) Fractures of the odontoid process of the axis. *J Bone Jt Surg Am* 86:2081
23. Grauer JN, Shafi B, Hilibrand AS et al (2005) Proposal of a modified, treatment-oriented classification of odontoid fractures. *Spine J* 5:123–129
24. Sasso RC (2001) C2 dens fractures: treatment options. *J Spinal Disord* 14:455–463
25. Chapman J, Smith JS, Kopjar B et al (2013) The AOSpine North America Geriatric Odontoid Fracture Mortality Study: a retrospective review of mortality outcomes for operative versus nonoperative treatment of 322 patients with long-term follow-up. *Spine* 38:1098–1104
26. Molinari RW, Dahl J, Gruhn WL et al (2013) Functional outcomes, morbidity, mortality, and fracture healing in 26 consecutive geriatric odontoid fracture patients treated with posterior fusion. *J Spinal Disord Tech* 26:119–126
27. Patel A, Zakaria R, Al-Mahfoudh R et al (2015) Conservative management of type II and III odontoid fractures in the elderly at a regional spine centre: a prospective and retrospective cohort study. *Br J Neurosurg* 29:249–253
28. Müller EJ, Schwinnen I, Fischer K et al (2003) Non-rigid immobilisation of odontoid fractures. *Eur Spine J* 12:522–525
29. Theologis AA, Deviren V, Tay B (2017) Temporary fusionless posterior occipitocervical fixation for a proximal junctional type II odontoid fracture after previous C2-pelvis fusion: case report, description of a new surgical technique, and review of the literature. *Eur Spine J* 26:243–248
30. Guo Q, Deng Y, Wang J et al (2016) Comparison of clinical outcomes of posterior C1–C2 temporary fixation without fusion and C1–C2 fusion for fresh odontoid fractures. *Neurosurgery* 78:77–83
31. Han B, Li F, Chen G et al (2015) Motion preservation in type II odontoid fractures using temporary pedicle screw fixation: a preliminary study. *Eur Spine J* 24:686–693
32. Koller H, Resch H, Acosta F et al (2010) Assessment of two measurement techniques of cervical spine and C1–C2 rotation in the outcome research of axis fractures: a morphometrical analysis using dynamic computed tomography scanning. *Spine* 35:286–290
33. Capek L, Rehousek P, Henys P et al (2020) Cement augmentation of odontoid peg fractures: the effect of cement volume and distribution on construct stiffness. *Eur Spine J* 29:977–985
34. Schwarz F, Lawson McLean A et al (2018) Cement-augmented anterior odontoid screw fixation in elderly patients with odontoid fracture. *Clin Neurol Neurosurg* 175:144–148
35. Kohlhof H, Seidel U, Hoppe S et al (2013) Cement-augmented anterior screw fixation of Type II odontoid fractures in elderly patients with osteoporosis. *Spine J* 13:1858–1863
36. Ramazanoğlu AF, Sarıkaya C, Etlı MU et al (2022) Results of percutaneous cervical vertebroplasty using an anterolateral approach for cervical spine tumors. *Acta Orthop Traumatol Turc* 56:268–271
37. Anselmetti GC, Manca A, Montemurro F et al (2012) Vertebroplasty using transoral approach in painful malignant involvement of the second cervical vertebra (C2): a single-institution series of 25 patients. *Pain Phys* 15:35–42
38. Kordecki K, Lewszuk A, Puławska-Stalmach M et al (2015) Vertebroplasty of cervical vertebra. *Pol J Radiol* 80:51–56
39. Brage L, Roldán H, Plata-Bello J et al (2016) Transoral vertebroplasty for a C2 aneurysmal bone cyst. *Spine J* 16:e473–477
40. Kaminsky IA, Härtl R, Sigounas D et al (2013) Transoral C2 biopsy and vertebroplasty. *Interv Med Appl Sci* 5:76–80
41. Martin J-B, Gailloud P, Dietrich P-Y et al (2002) Direct transoral approach to C2 for percutaneous vertebroplasty. *Cardiovasc Intervent Radiol* 25:517–519
42. Monterumici DAF, Narne S, Nena U et al (2007) Transoral kyphoplasty for tumors in C2. *Spine J* 7:666–670
43. Reddy AS, Dinobile D, Orgeta JE et al (2009) Transoral approach to CT-guided C2 interventions. *Pain Phys* 12:253–258
44. Montero-Odasso MM, Kamkar N, Pieruccini-Faria F et al (2021) Evaluation of clinical practice guidelines on fall prevention and management for older adults: a systematic review. *JAMA Netw Open* 4:e2138911

45. O’Leary PT, Bridwell KH, Lenke LG et al (2009) Risk factors and outcomes for catastrophic failures at the top of long pedicle screw constructs: a matched cohort analysis performed at a single center. *Spine (Phila Pa 1976)* 34:2134–2139

Publisher’s Note Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.