Journal of Clinical Neuroscience 119 (2024) 85–92

Contents lists available at ScienceDirect

Journal of Clinical Neuroscience

journal homepage: www.journals.elsevier.com/journal-of-clinical-neuroscience

Long-term outcomes in patients treated with tissue-sparing posterior cervical fusion to revise a 1-level pseudarthrosis following ACDF

Michael M. Haglund [a,*], Bruce M. McCormack [b], Daniel M. Williams [c], Alexander C. Lemons [c], Erik M. Summerside [d]

[a] Department of Neurosurgery, Duke University School of Medicine, Durham, NC, USA
[b] Department of Neurosurgery, University of San Francisco, San Francisco, CA, USA
[c] Pinehurst Surgical Clinic, Pinehurst, NC, USA
[d] Department of Clinical Affairs, Providence Medical Technology, Pleasanton, CA, USA

ARTICLE INFO

Keywords:
Cervical
Pseudarthrosis
Non-union
Revision
PCF
Tissue sparing
Facet instrumentation

ABSTRACT

Study Design: Observational Study
Background: Symptomatic pseudarthrosis is one long-term complication in patients treated with anterior discectomy and fusion (ACDF). When revising a pseudarthrosis, a surgeon must decide to intervene posteriorly and/or anteriorly. Open posterior cervical fusion (PCF) is attractive for high rates of arthrodesis, however this technique introduces risks of added complications resulting from extensive soft tissue dissection. The purpose of this study was to assess long-term outcomes in patients undergoing tissue-sparing PCF with facet instrumentation to treat a single level pseudarthrosis.
Methods: Forty-five subjects were recruited from six participating sites. All subjects had a history of ACDF that was subsequently revised with tissue-sparing PCF to treat symptomatic pseudarthrosis at one level. Long-term radiographic assessments included flexion and extension X-ray and multi-planar CT. Subjects additionally completed a patient satisfaction questionnaire. Radiographs were assessed by investigators and an independent core imaging lab to diagnose implant integrity and arthrodesis at the revised levels.
Results: The revision procedure required a median 49 min to complete with an estimated blood loss of 10 cc. Subjects were discharged a median 1 day following treatment. There were no instances of hospital re-admission nor subsequent surgical interventions. Study follow-up assessments were performed a median 39 months from revision. Surgeons diagnosed complete fusion in 91 % of cases. The core imaging lab identified bridging bone across the revised segment in 80 % of cases. Range of motion was $< 2^{\circ}$ in 93 % of cases. Seventy-four percent of subjects reported being satisfied with their outcomes.
Conclusions: This study summarizes long-term radiographic outcomes in a cohort of patients receiving tissue-sparing PCF for the treatment of pseudarthrosis. Assessed years after revision, patients achieved rates of arthrodesis similar to open PCF without the soft tissue dissection responsible for perioperative morbidity and long-term soft tissue pain.

1. Introduction

Symptomatic pseudarthrosis is a known complication presenting in the months and years following anterior cervical fusion with an incidence rate of 10–50 %[1]. For surgeons routinely performing revisions for pseudarthrosis, an essential question is whether to redo the anterior fusion or provide supplemental open PCF.

Open PCF with lateral mass screw and rod fixation is an attractive approach for revision due to its reported rates of arthrodesis commonly exceeding 90 %[2]. Strong radiographic outcomes from PCF have not always correlated with improvements in clinical outcomes[3]. The technique introduces a greater incidence of peri- and postoperative complications when compared to ACDF [4–7]. One explanation for the discrepancy between radiographic and clinical outcomes is due to the collateral soft tissue damage resulting from PCF. Open PCF requires stripping the paraspinal muscles off the spine and retracting these tissues

* Corresponding author.
E-mail address: Michael.Haglund@duke.edu (M.M. Haglund).

https://doi.org/10.1016/j.jocn.2023.11.020
Received 5 October 2023; Accepted 13 November 2023

Table 1
Eligibility criteria for participation in follow-up assessments.

Inclusion Criteria	18 years of age or older
	Received PCF surgery with tissue sparing facet fusion prior to 10/31/2020 to revise a past ACDF
	Treated levels are between C3-C7
	Included single level symptomatic pseudarthrosis as indication for revision
Exclusion Criteria	Any revision procedures that involved laminectomy or corpectomy
	Any revision procedure that involved implanting or removing supplemental posterior constructs from lateral mass fixation such as lateral mass rods, screws, or wires

for lateral mass bone exposure. This exposure leads to longer surgery time, more bleeding, lengthier hospital stays, and higher complication rates compared to other techniques[5,8–11]. A *meta*-analysis by Medvedev et al.[12] tracked re-admission and re-operation rates in patients receiving open PCF and reported the most common reason for revision was surgical wound infection. In the long-term, persistent moderate to severe pain has been reported in 48 % of patients with open PCF to revise a pseudarthrosis despite a solid arthrodesis[13]. Myofascial injury from soft tissue dissection and retraction is one factor causing chronic pain in these patients. It is this reason surgeons may opt for observation, particularly if the complaints are mild. Others may choose to minimize soft tissue dissection by performing a redo ACDF, though bone healing is less predictable[11].

Minimally invasive spine surgery techniques can achieve the same therapeutic results as standard open surgery with less cost[14]. Tissue-sparing PCF with facet instrumentation is one technique that has been shown to provide promising clinical results for the treatment of cervical degenerative disc disease[15–17]. Smith et al.[18] were the first to report this technique for the treatment of symptomatic cervical pseudarthrosis. The authors reported clinically meaningful improvements in NDI for 80 % of cases with reduced perioperative morbidity compared to standard open PCF. Radiographic follow-up in their study was encouraging, but CT imaging was not available in many cases and the average follow-up was limited at 18 months.

The goal of the current study was to assess long-term clinical and radiographic outcomes in patients undergoing tissue-sparing PCF with facet instrumentation to treat a single level symptomatic pseudarthrosis.

2. Methods

2.1. Patient cohort

The cohort for this analysis was informed from a retrospective chart review performed across six clinic sites located in the United States. Medical records were reviewed for surgical cases meeting eligibility criteria defined in Table 1. Subjects were identified and contacted by a third-party company enlisted by the investigators (DoctorPlan, Sausalito, CA, USA). Subjects were contacted through e-mail, phone, and/or Participating subjects received monetary compensation.

A total 45 subjects provided written consent to participate in follow-up study assessments. Informed consent and all follow-up assessments were conducted in accordance with 45 CFR Part 46 as approved by an institutional review board (E&I Review Services, Study# 21109–02; Duke University Health System, Study# Pro00109378).

Subject medical records were summarized to include demographics as well as details of symptoms, surgical interventions, and clinical outcomes surrounding both index ACDF procedure and subsequent PCF procedure. Demographic information was recorded at time of PCF revision.

2.2. PCF surgical technique

All subjects received PCF with a facet instrumentation to treat a symptomatic pseudarthrosis at 1 level. This surgical technique has been previously described in detail[19], but is briefly summarized here. After general anesthesia, the patient is positioned prone with their neck aligned in a neutral position. Shoulders are pulled down with tape. Biplanar fluoroscopy is positioned for AP and lateral views. A longitudinal incision is made through the sub-cutaneous fascia and paraspinal muscle inferior to the intended spinal level to provide direct trajectory to the facet joint. Incision can be as small as 1.5 cm, but also much larger depending upon the surgeon's experience and preference. The facet joint is accessed with a tool which serves as a post for a rotatory decorticator which is applied to the lateral mass (Fig. 1). The decorticator is removed. A guide tube is then inserted over the access tool under the fluoroscopic guidance. The access tool is removed and various rasps and decorticators are used to decorticate the facet joint. The facet joint is stabilized using a titanium cage in conjunction with a bone screw (CAVUX Facet Fixation System, Providence Medical Technology, Pleasanton, CA). The cage is filled with demineralized bone graft and impacted into the facet with a small mallet under fluoroscopy. The bone screw is threaded through the

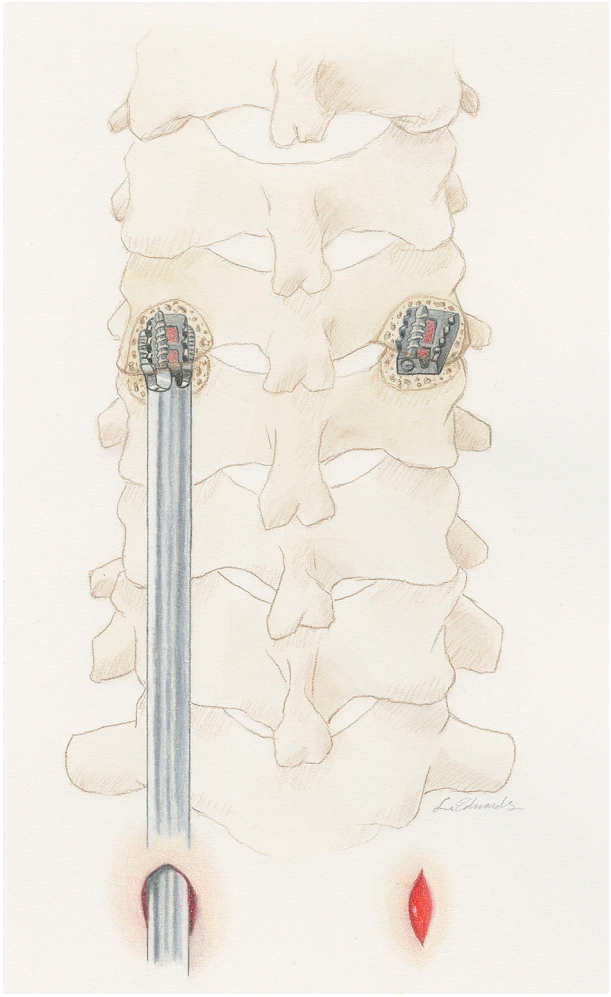

Fig. 1. Tissue-sparing PCF. The lateral mass is decorticated to prepare the joint for fusion. An intrafacet cage with bone screw is delivered through a guide tube to provide temporary stabilization until fusion occurs.

cage into the lateral mass of the superior level. Bone graft is then delivered through the guide tube onto the decorticated lateral mass surface. The guide tube is removed, the wound is closed, and the procedure is repeated on the contralateral facet joint.

2.3. Radiographic assessments

Subjects had cervical x-rays with lateral flexion and extension films and a multi-planar cervical CT scan. Each set of images was analyzed by study investigators to determine the presence of fusion (clinical impression by investigator), cage migration (25 %-50 % movement from initial position), cage expulsion (>50 % movement from initial position), and cage loosening (radiolucency around hardware/bone interface), as well as a narrative summary providing rational for these assessments.

An independent core radiographic imaging laboratory (Medical Metrics Inc., Houston, TX, USA) additionally reviewed all images to quantify segmental angular range of motion using validated quantitative motion analysis software[20,21] and to determine presence of contiguous trabecular bridging bone across the vertebral endplate and facets. Bridging bone was determined by two board-certified radiologists with incongruent outcomes being adjudicated by a third radiologist.

2.4. Long-term clinical assessments

Clinical success was determined though completion of treatment satisfaction questionnaires. Participants had an option of selecting *extremely satisfied, somewhat satisfied, neither satisfied nor unsatisfied, somewhat unsatisfied*, or *extremely unsatisfied*. A subject was considered a clinical success only if they selected *extremely satisfied*, or *somewhat satisfied* and were considered a failure if they selected *somewhat dissatisfied* or *extremely dissatisfied*. Agreement between radiographic and clinical outcomes was calculated using the following equation:

$$Agreement(\%) = \frac{Success_{rad}\&Success_{clin} + Failure_{rad}\&Failure_{clin}}{AllAssessments}$$

2.5. Statistical analysis

Summary statistics are presented as median and range. Outcomes are described as an entire cohort and by subgroups that varied based upon demographics and risk factors for pseudarthrosis. Subgroups include the following: nicotine use, age, and BMI. Categorical responses were assessed using a Fisher's Exact Test. All statistical tests are presented using a threshold of $\alpha = 0.05$.

3. Results

3.1. Subject demographics and ACDF operative details

Across all cases, the median age of the patient was 53 years (range 36–78 years) at time of revision and 60 % were female. The number of levels treated during the index ACDF ranged from 1 to 4 levels. Eighty-four percent of index ACDF cases included the use of an anterior plate. A detailed description of subject demographics and ACDF operative details is provided in Table 2.

3.2. PCF operative details

The median time between the index ACDF and revision PCF was 24 months (range 6–104). All revisions involved treatment between C3-C7 with the most common level revised being C6-C7 (47 % of revisions). The median operative time was 49 min (range 21–159). The median estimated blood loss was 10 cc (range 5–75), and the median hospital stay was 1 night (range 0–3). There were no instances of a revised level requiring a subsequent revision for persistent pseudarthrosis. Revision PCF operative details are summarized in Table 3.

Table 2
Demographic and ACDF operative details.

	All Subjects (n = 45)
Age (years)	53 (36–78)
Sex (females, %)	27 (60 %)
BMI	28 (17–59)
Workmen's Compensation	3
Nicotine Use	
Current	8
Former	11
Never	22
Not Answered	4
# of Levels Treated during ACDF	
1	15
2	15
3	11
4	2
Not Reported	2
Location of Levels Treated during ACDF	
C2-C3	1
C3-C4	7
C4-C5	18
C5-C6	30
C6-C7	30
ACDF Included Ant. Fixation Plate	
Yes	38
No	4
Not Answered	3

Table 3
PCF Operative details for revision of ACDF pseudarthrosis.

	All Subjects (n = 45)
Time from index ACDF to revision PCF (months)	24 (6–104)
Location of Levels Revised	
C3-C4	4
C4-C5	7
C5-C6	13
C6-C7	21
Operative Duration (minutes)	49 (21–159)
Blood Loss (cm^3)	10 (5–75)
Nights in Hospital	1 (0–3)

3.3. Radiographic outcomes

The median time from revision surgery to acquisition of study images was 39 months with the shortest follow-up completed at 14 month following revision and the longest being 76 months. A total 84 % of subjects had a minimum of 24 months between revision and study follow-up images.

Investigators diagnosed persistent pseudarthrosis in 9 % of cases reviewed with the rational provided in Appendix A. There were 3 instances of device loosening with radiolucency around the implant. There was no device migration or expulsion and no instances of facet cage or screw fracture. The core imaging lab reported evidence of bridging bone in 80 % of subjects (across the interbody endplate and/or both facets). A ROM of $< 2^\circ$ was reported in 93 % of subjects. The core imaging lab identified a presence of *both* contiguous bridging bone and ROM $< 2^\circ$ in 80 % of subjects (composite fusion success, n = 35/44). Of the 9 composite failures, 3 demonstrated a ROM $\geq 2^\circ$ (33 %) and all included a lack of evidence of bridging bone (100 %). The comorbidities tracked in this study had no observable influence on any radiographic outcomes (Table 4).

In one case, an investigator was unable to determine fusion status (Appendix A). In a separate case, the core imaging lab was unable to measure ROM due to obstructed anatomy at C6-C7. In total, there were 44 cases with investigator impressions, 45 cases for bridging bone, 44 cases for ROM, and 44 cases for composite fusion success. Radiographic

Table 4
Radiographic outcomes from investigators and independent core imaging laboratory.

	Investigator Determined Fusion	$BBone_{either}$	$BBone_{body}$	$BBone_{facets}$	ROM	Composite ($BBone_{either}$ and ROM)
All Assessments	40/44 (91 %)	36/45 (80 %)	32/45 (71 %)	31/45 (69 %)	41/44 (93 %)	35/44 (80 %)
Level Revised						
C3-C4	3/3	3/4	3/4	2/4	4/4	3/4
C4-C5	7/7	6/7	5/7	6/7	7/7	6/7
C5-C6	10/13	10/13	9/13	10/13	12/13	10/13
C6-C7	20/21	17/21	15/21	13/21	18/20	16/20
p	0.40	1.00	1.00	0.52	1.00	1.00
Nicotine Use						
Current	7/8	5/8	4/8	3/8	5/7	4/7
Past	11/11	10/11	9/11	9/11	11/11	10/11
Never	19/22	18/22	16/22	16/22	21/22	18/22
Not Answered	3/3	3/4	3/4	3/4	4/4	3/4
p	0.63	0.48	0.49	0.21	0.16	0.36
Age						
<65 years	35/39	32/39	29/39	27/39	36/38	31/38
≥ 65 years	5/5	4/6	3/6	4/6	5/6	4/6
p	1.00	0.58	0.33	1.00	0.36	0.59
BMI						
<30	23/26	23/27	19/27	21/27	26/27	23/27
≥ 30	15/16	12/16	12/16	9/16	14/15	11/15
Not Answered	2/2	1/2	1/2	1/2	1/2	1/2
p	1.00	0.26	0.75	0.21	0.17	0.26

BBone = bridging bone on CT, *body* = across interbody, *facets* = across both facets, *either* = across either interbody or both facets, *ROM* = segmental range of motion < 2° on dynamic X-ray.

outcomes are summarized in Table 4.

There were 43 cases including decision by both the investigator and independent imaging lab. There was agreement between investigator impressions of fusion and composite fusion success in 35 of 43 cases (81 %). Unanimous fusion was reported in 33 subjects and unanimous pseudarthrosis in 2 subjects. There was disagreement in 8 cases (Investigator Success&Composite Failure = 6, Investigator Failure&Composite Success = 2).

3.4. Clinical outcomes

All but one subject participating in long-term radiographic assessments completed a treatment satisfaction survey (n = 44/45). Clinical success was reported in 75 % of subjects (*Extremely Satisfied* or *Somewhat Satisfied*) and was independent of radiographic outcomes (Table 5).

Agreement between composite radiographic outcomes and clinical outcomes was 65 % (Table 5, n = 28/43). Agreement between investigator determined radiographic outcomes and clinical outcomes was 74 % (n = 32/43).

3.5. Adverse events and persistent radiographic pseudarthroses

No subject required hospital re-admission nor subsequent surgical interventions at levels revised with PCF. There was one observed adverse event (2.2 %) where a subject complained of new onset bilateral numbness and tingling of the hands at 26 days post revision (described in case report below). The symptoms resolved after treatment with muscle relaxers and Tylenol.

Nine subjects were diagnosed with radiographic pseudarthrosis at time of study follow up. These subjects are described in detail in Table 6. Seven subjects reported satisfaction with pain relief reported at time of study follow-up. Of these, six had segmental ROM < 2°. Two subjects (22 %) reported being extremely dissatisfied and were active nicotine users. Unsatisfied subjects had a segmental ROM > 2°. Their post-revision treatments included prescription pain medication, but neither received subsequent injections or surgical revisions.

3.6. Case report

A 53 y/o female (BMI = 32 kg/m^2) with no documented comorbidities presented to the investigator in early 2018 with complaints of

Table 5
Agreement between radiographic outcomes and clinical outcomes.

	Composite Success ($Success_{rad}$)	Composite Failure ($Failure_{rad}$)	Investigator Determined ($Success_{rad}$)	Investigator Determined ($Failure_{rad}$)
Extremely Satisfied	12	3	13	1
Somewhat Satisfied	14	3	17	1
Neither satisfied nor dissatisfied	2	1	3	0
Somewhat dissatisfied	3	0	3	0
Extremely dissatisfied	3	2	3	2
p	0.67		0.29	
All Assessments*	43			
Clinical Success ($Success_{clin}$)	26	6	30	2
Clinical Failure ($Failure_{clin}$)	6	2	6	2
p	0.65		0.17	

*One subject with radiographic success did not complete questionnaires.

Table 6
Treatment details of nine subjects with persistent radiographic pseudarthrosis according to composite fusion definition.

Index ACDF	PCF Revision	Follow-up (months)	ROM (degrees)	Pain Satisfaction	Post-op Pain Medication	SSI
C6-C7	C6-C7	32	3.7	Extremely Dissatisfied	Yes	No
C5-C6 C6-C7	C6-C7	39	0.8	Extremely Satisfied	No	No
C5-C6 C6-C7	C6-C7	39	1.9	Extremely Satisfied	Yes	No
C4-C5 C5-C6 C6-C7	C6-C7	26	3.6	Satisfied	No	No
C5-C6 C6-C7	C5-C6	23	2.7	Extremely Dissatisfied	Yes	No
C3-C4	C3-C4	21	1.6	Extremely Satisfied	No	No
C5-C6 C6-C7	C5-C6	19	1.3	Neither Satisfied nor Dissatisfied	Yes	No
C4-C5 C5-C6 C6-C7	C4-C5	14	1.9	Satisfied	No	No
C5-C6	C5-C6	40	1.3	Satisfied	Yes	No

cervical radiculopathy. Their index surgery involved 1-level ACDF at C5-C6 with allograft bone and anterior plate. Their prognosis was positive as of their last post-operative visit (4 months). The patient returned with recurrent symptoms two years later. Imaging studies confirmed a pseudarthrosis at C5-C6 (Fig. 2) and surgical revision was recommended.

The PCF revision with facet instrumentation at C5-C6 was performed in September 2020. Estimated blood loss was 10 cc. The patient was discharged the same day without the need for prescription pain medication. At their 6-week follow-up the patient complained of minor numbness of tingling in their arm, which resolved with muscle relaxers and Tylenol. In December 2021, the patient was contacted and agreed to participate in study prescribed follow-up assessments. Based on the radiographic evidence collected at study follow-up, both the investigator and independent imaging lab confirmed the presence of bridging bone across all assessed anatomy (interbody and bilateral facets, Fig. 2) and segmental range of motion at the revised level was 0.1°. The subject reported they were *extremely satisfied* with the pain relief following revision and further reported no numbness, weakness, or restrictions with their ability to perform daily chores.

4. Discussion

This study summarized long-term radiographic outcomes in a cohort of patients treated with PCF to revise a single level pseudarthrosis. Posterior cervical fusion performed with a tissue sparing technique achieved arthrodesis and long-term satisfaction with neck pain relief.

Revision with open PCF achieves high fusion rates but successful clinical outcomes are less assured. This incongruity is presented by McAnany et al.[3] who pooled clinical and radiographic outcomes from 10 studies where patients were revised with open PCF to address a pseudarthrosis following ACDF. Across these studies they reported a pooled fusion rate of 97 %, however pooled clinical success was achieved at a rate of only 72 %. Three possible causes of this discrepancy between fusion rates and patient outcomes include (1) lack of clarity in what is causing presenting pain, (2) poor sensitivity of x-ray imaging to diagnose pseudarthrosis, and (3) acute and chronic pain secondary to paraspinal muscle dissection in standard PCF.

4.1. Difficulty in identifying source of pain

Outcomes following repair of a radiographic pseudarthrosis will only be favorable if the pseudoarthrosis is the source of pain. A successful revision of pseudarthrosis also depends on how sound the clinical indications were for the index ACDF. Best case scenario for revision is a patient with good initial outcome who subsequently worsens with radiographic non-union and no other identifiable sources of pain. Those patients with poor initial results after ACDF are unlikely to have a positive response to pseudarthrosis revision. Often revisions are performed by a second surgeon unaware of the original indications and clinical course of the index procedure. In the current study for example, 90 % of one author's patients had their index procedure performed by a different surgeon.

Many pseudarthroses can be asymptomatic or minimally symptomatic with non-localizing axial neck pain that is difficult to discern from adjacent segment disease or myofascial pain syndromes. Fourteen percent of patients who achieved composite fusion success in this study still did not achieve satisfactory pain relief. These poor clinical outcomes could be attributed a lack of clarity on what was generating the complaint.

4.2. Poor sensitivity in X-ray for determining arthrodesis after PCF

The published medical literature on pseudarthrosis repair commonly include radiographic X-ray, but lack post-operative CT as evidence for determining fusion[22]. X-rays are an efficient and affordable assessment acquired during routine follow-ups and subsequently are relied on to determine fusion in most published case series on PCF revisions [13,23–27]. Imaging collected for this study involved both dynamic x-rays and CT with reconstruction for every patient. Films were interpreted by both the investigators and an independent core lab consisting of up to three board certified radiologists. To the authors' knowledge, this is the first study to incorporate this rigorous assessment of long-term fusion success to understand revision outcomes with PCF.

An important consideration when relying exclusively on x-rays is their poor sensitivity for identifying pseudarthroses (high rates of false negatives). Ghiselli et al.[28] highlighted this issue by comparing diagnosed cervical pseudarthrosis from dynamic x-rays against CT and confirmed these decisions against intraoperative exploration. They found a standard 2° ROM threshold for diagnosing pseudarthrosis had only half the sensitivity when compared to CT (ROM:38.5 % vs. CT:69.1 %). Similarly, Ploumis et al.[29] compared rates of pseudarthrosis diagnosed between X-ray and CT and found that rates were 11 % higher with reading CT (X-ray = 11 % not fused; CT = 22 % not fused). Skolasky et al.[30] found surgeons reviewing x-rays were more likely to miss a pseudarthrosis if the patient reported improvements in pain at the time.

When comparing fusion outcomes from different imaging sources in the current study, pseudarthrosis was identified more frequently using CT (20 %) when compared to ROM thresholds (7 %). These differences suggest that a radiographic fusion assessment relying on x-rays alone may miss a meaningful number of radiographic pseudarthroses that are presenting in follow-up clinical assessments.

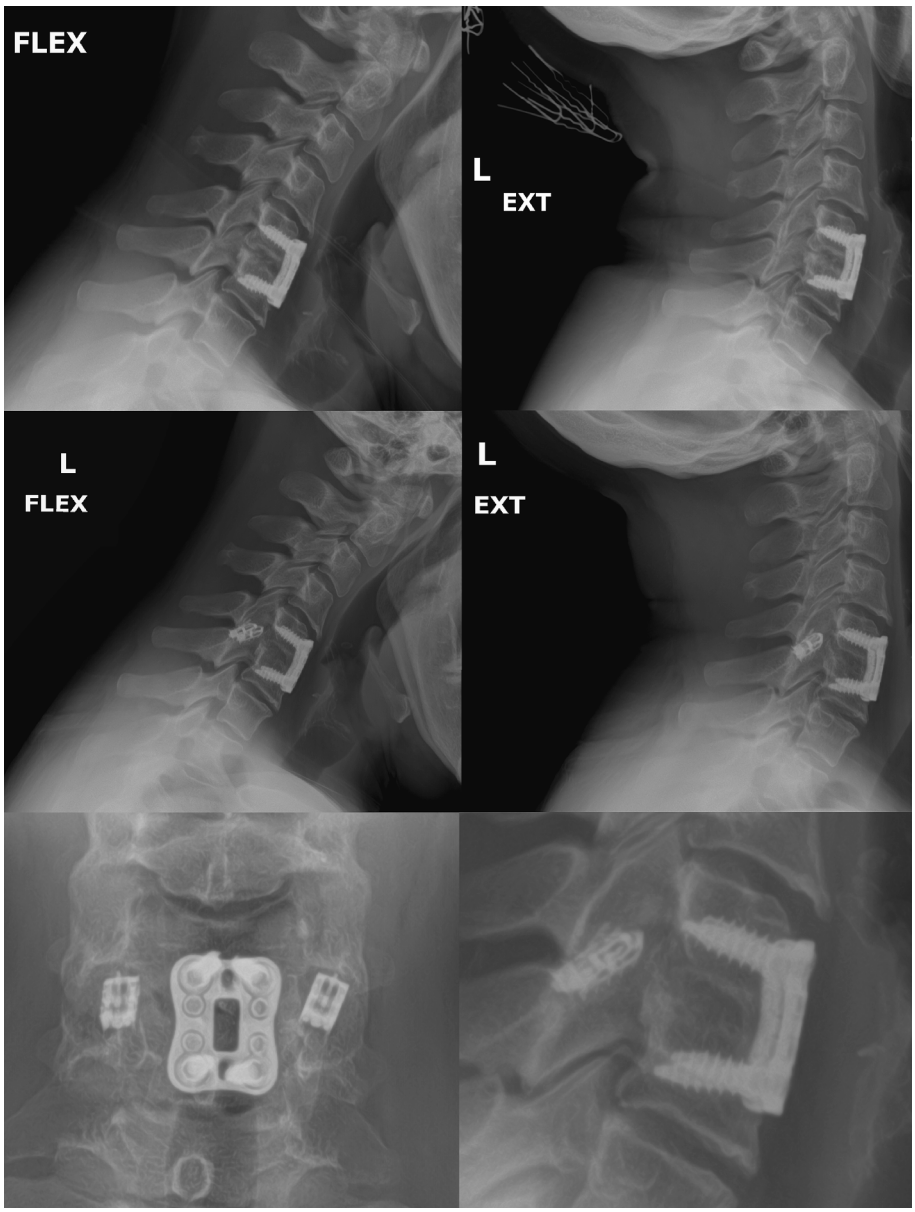

Fig. 2. Study images collected at revision pre-op (top) and at 15 months following revision procedure (middle, bottom).

4.3. Minimizing peri-operative costs improve clinical outcomes

The *peri*-operative morbidity of PCF revision is significant and may in some cases exceed the burden of the symptoms stemming from pseudarthrosis. If a patient's complaints are mild or the source of pain is difficult localize, a surgeon may be reluctant to revise with PCF despite reliable fusion rates. PCF requires dissecting and retracting the paraspinal muscles typically for a level or two above and below the level of arthrodesis to obtain necessary exposure for decortication and instrumentation. Most surgeons currently use lateral mass screws and rods. This prominent hardware can irritate overlying soft tissue, introducing a further source of chronic pain. Carreon et al.[11] presented *peri*-operative data on 120 patients who had revision of pseudarthrosis involving either a repeat ACDF or open PCF. The average number of levels revised was 1.5 matched between groups. Patients receiving a PCF revision had higher rates of fusion than ACDF, but had over twice the amount of blood lost (ACDF = 103 cm^3; PCF = 282 cm^3) and required an additional 2 nights in the hospital before discharge (ACDF = 1.3 nights; PCF = 3.4 nights). The operative duration was similar between approaches (ACDF = 135 min; PCF = 139 min). The tissue sparing approach utilized in the current study required a median operative duration of 43 min and accrued an estimated blood loss of 10 cc Subjects were discharged a median 1 day after surgery. There were no documented hospital readmissions in the 90 days following discharge and no subsequent revisions for persistent pseudarthrosis.

Smith et al[18] performed tissue-sparing PCF on patients with symptomatic pseudarthrosis following a failed ACDF and tracked clinical improvements for VAS_{arm}, VAS_{neck}, and NDI over an average of 18 months following revision. They reported clinically meaningful improvements in 80 %, 72 %, and 80 % respectively. In the current study, neither VAS nor NDI scores were reported however all participants completed a treatment satisfaction questionnaire. Across all participants, 73 % indicated they were either extremely or somewhat satisfied. Most importantly, these satisfaction outcomes agreed with investigator assessments.

4.4. Contraindications for tissue-sparing PCF

Tissue sparing PCF with facet instrumentation is a potential treatment option for the vast majority of pseudarthrosis, however there are exceptions where a standard open PCF with lateral mass screws or repeat anterior approach is advantageous. If the pseudarthrosis is between long fusion masses encompassing several spinal levels, lateral mass fixation at multiple levels would be required to achieve mechanical stability at the revised level. Prior foraminotomy at an index level would preclude facet cage fixation. If there is a large bony gap at the pseudarthrosis, displaced anterior hardware, kyphosis, or symptomatic ventral nerve compression, then facet fixation alone would not be appropriate or would have to be combined with an anterior reconstruction.

5. Limitations

This study is based on a limited sample of subjects from a small group of surgeons. As a result, there is a risk that subjects participating may not accurately represent the broader population of patients treated with revision PCF. A poor experience between the patient and investigator may have influenced whether a patient chose to participate, however this is likely not a large influence as the study assessments did not involve any direct interactions with the surgeons nor medical care of any kind from the sites.

An investigator reviewing their own patients' radiographs introduces the possibility of an inherent bias to diagnose a favorable outcome, particularly when the diagnosis is made in the absence of any complaints of pain. Of the different criteria used to determine radiographic success, surgeon impressions had the highest fusion rates. In an attempt to mitigate this confound, an independent core imaging lab was employed to review all collected X-rays and CTs. When comparing decisions between the investigator and independent lab, agreement was observed in 81 % of cases. Additionally, investigator impressions had strong agreement with clinical success, suggesting that any bias introduced by the investigators was minimal in influencing study conclusions.

6. Conclusions

This study summarizes an assessment of long-term outcomes in patients receiving a PCF for the treatment of symptomatic pseudarthrosis. In this cohort, PCF performed through a tissue-sparing technique had positive *peri*-operative costs, comparable rates of fusion as reported through open PCF techniques, and relieved pain when assessed in the years following surgery. The collection of both dynamic x-rays with CT highlights a significant improvement in sensitivity to diagnose pseudarthrosis over previously published case series, with x-rays alone under reporting radiographic failures. Furthermore, using multiple image sources led to an improvement in reconciling the differences between radiographic and clinical outcomes previously reported for revision PCF.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by Providence Medical Technology.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: This study was funded by Providence Medical technology (PMT). Dr. McCormack has a financial interest in PMT. Dr. Summerside is an employee of PMT. Drs Haglund, Williams, and Lemons have no financial interested that would be impacted by outcomes reported in this study.

Acknowledgements

The authors would like to acknowledge Drs. Randall Seago, Michael Leahy, Jeffrey Lewis, and Joseph Serghany as well as Karen Grace, Neric Guinn, Lisa Gregory, Courtney Elliot, Rachel Kistner, and Stephanie Huang.

References

[1] Zuckerman SL, Devin CJ. Pseudarthrosis of the cervical spine. Clin Spine Surg 2022;35(3):97–106.
[2] Youssef JA, Heiner AD, Montgomery JR, et al. Outcomes of posterior cervical fusion and decompression: a systematic review and meta-analysis. Spine J 2019;19(10):1714–29.
[3] McAnany SJ, Baird EO, Overley SC, Kim JS, Qureshi SA, Anderson PA. A meta-analysis of the clinical and fusion results following treatment of symptomatic cervical pseudarthrosis. Global Spine J 2015;5(2):148–55.
[4] Leckie S, Yoon ST, Isaacs R, et al. Perioperative complications of cervical spine surgery: analysis of a prospectively gathered database through the association for collaborative spinal research. Global Spine J 2016;6(7):640–9.
[5] Badiee RK, Mayer R, Pennicooke B, Chou D, Mummaneni PV, Tan LA. Complications following posterior cervical decompression and fusion: a review of incidence, risk factors, and prevention strategies. J Spine Surg 2020;6(1):323–33.
[6] Memtsoudis SG, Hughes A, Ma Y, Chiu YL, Sama AA, Girardi FP. Increased in-hospital complications after primary posterior versus primary anterior cervical fusion. Clin Orthop Relat Res 2011;469(3):649–57.
[7] Badhiwala JH, Ellenbogen Y, Khan O, et al. Comparison of the inpatient complications and health care costs of anterior versus posterior cervical decompression and fusion in patients with multilevel degenerative cervical myelopathy: a retrospective propensity score-matched analysis. World Neurosurg 2020;134:e112–9.
[8] Deng H, Yue JK, Ordaz A, Rivera EJ, Suen CG, Sing DC. Cervical fusion for degenerative disease: A comprehensive cost analysis of hospital complications in the United States from 2002 to 2014. J Craniovertebr Junction Spine 2018;9(3):140–7.
[9] Fehlings MG, Smith JS, Kopjar B, et al. Perioperative and delayed complications associated with the surgical treatment of cervical spondylotic myelopathy based on 302 patients from the AOSpine North America Cervical Spondylotic Myelopathy Study. J Neurosurg Spine 2012;16(5):425–32. Epub 2012 Feb 10. *Spine J*. 2012;12(4):352.
[10] Furlan JC, Kalsi-Ryan S, Kailaya-Vasan A, Massicotte EM, Fehlings MG. Functional and clinical outcomes following surgical treatment in patients with cervical spondylotic myelopathy: a prospective study of 81 cases. J Neurosurg Spine 2011;14(3):348–55.
[11] Carreon L, Glassman SD, Campbell MJ. Treatment of anterior cervical pseudoarthrosis: posterior fusion versus anterior revision. Spine J 2006;6(2):154–6.
[12] Medvedev G, Wang C, Cyriac M, Amdur R, O'Brien J. Complications, readmissions, and reoperations in posterior cervical fusion. Spine 2016;41(19):1477–83.
[13] Kuhns CA, Geck MJ, Wang JC, Delamarter RB. An outcomes analysis of the treatment of cervical pseudarthrosis with posterior fusion. Spine 2005;30(21):2424–9.
[14] Vaishnav AS, Othman YA, Virk SS, Gang CH, Qureshi SA. Current state of minimally invasive spine surgery. J Spine Surg 2019;5(Suppl 1):S2–10.
[15] Laratta JL, Gupta K, Smith WD. Tissue-sparing posterior cervical fusion with interfacet cages: A systematic review of the literature. Global Spine J 2020;10(2):230–6.
[16] Yazdanshenas H, Osias E, Hwang R, Park DY, Lord E, Shamie AN. Retrospective evaluation of cervical fusion with DTRAX (R) cervical cage. J Craniovertebr Junction Spine 2022;13(1):48–54.
[17] Ramos MRD, Mendoza CJP, Yumol JV, Joson RS, Ver MLP, Ver MR. Multilevel, percutaneous posterior cervical interfacet distraction and fusion for cervical spondylotic radiculopathy: clinical and radiographic outcomes. Spine 2021;46(21):E1146–54.
[18] Smith W, Gillespy M, Huffman J, Vong V, McCormack BM. Anterior cervical pseudarthrosis treated with bilateral posterior cervical cages. Oper Neurosurg (Hagerstown) 2018;14(3):236–42.
[19] Summerside E, Heller J, Glenn J, McCormack B, Menchetti PPM. Tissue sparing posterior fixation as a treatment option for degenerative disc disease. In: Menchetti PPM, editor. Cervical Spine: Minimally Invasive and Open Surgery. Cham: Springer International Publishing; 2022. p. 231–45.
[20] Zhao K, Yang C, Zhao C, An K-N. Assessment of non-invasive intervertebral motion measurements in the lumbar spine. J Biomech 2005;38(9):1943–6.
[21] Reitman CA, Hipp JA, Nguyen L, Esses SI. Changes in segmental intervertebral motion adjacent to cervical arthrodesis: a prospective study. Spine 2004;29(11):E221–6.
[22] Goldstein C, Drew B. When is a spine fused? Injury 2011;42(3):306–13.
[23] Brodsky AE, Khalil MA, Sassard WR, Newman BP. Repair of symptomatic pseudoarthrosis of anterior cervical fusion. Posterior versus anterior repair. Spine 1992;17(10):1137–43.
[24] Farey ID, McAfee PC, Davis RF, Long DM. Pseudarthrosis of the cervical spine after anterior arthrodesis. Treatment by posterior nerve-root decompression, stabilization, and arthrodesis. J Bone Joint Surg Am 1990;72(8):1171–7.

[25] Gore DR, Brechbuler M. Treatment of nonunions following anterior cervical discectomy and fusion with interspinous wiring and bone grafting. J Surg Orthop Adv 2003;12(4):214–7.
[26] Lowery GL, Swank ML, McDonough RF. Surgical revision for failed anterior cervical fusions. Articular pillar plating or anterior revision? Spine 1995;20(22): 2436–41.
[27] Toohey JS, Stromberg L, Neidre A, Ramsey M, Fogel GR. Treatment of cervical pseudarthrosis after Smith-Robinson procedure with Halifax clamp fixation. J Surg Orthop Adv 2006;15(4):201–2.
[28] Ghiselli G, Wharton N, Hipp JA, Wong DA, Jatana S. Prospective analysis of imaging prediction of pseudarthrosis after anterior cervical discectomy and fusion: computed tomography versus flexion-extension motion analysis with intraoperative correlation. Spine 2011;36(6):463–8.
[29] Ploumis A, Mehbod A, Garvey T, Gilbert T, Transfeldt E, Wood K. Prospective assessment of cervical fusion status: plain radiographs versus CT-scan. Acta Orthop Belg 2006;72(3):342–6.
[30] Skolasky RL, Maggard AM, Hilibrand AS, et al. Agreement between surgeons and an independent panel with respect to surgical site fusion after single-level anterior cervical spine surgery: a prospective, multicenter study. Spine 2006;31(15): E503–6.