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Invited Review

Diagnosing Pseudoarthrosis After Anterior Cervical Discectomy and Fusion

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Radiographic confirmation of fusion after anterior cervical discectomy and fusion (ACDF) surgery is a critical aspect of determining surgical success. However, there is a lack of established diagnostic radiographic parameters for pseudoarthrosis. The purpose of this study is to summarize the findings of previous studies, review the advantages and disadvantages of frequently employed diagnostic criteria, and present our recommended protocol of fusion assessment. This study identified randomized controlled trials, case-control studies, and prospective and retrospective cohort studies reporting on spinal fusion and how successful fusion after ACDF. Among the 39 articles reviewed, bridging bone across the operated levels on static radiographs was the most commonly used criteria to confirm fusion (31 of 39, 79%). Dynamic flexion-extension radiographs were used to assess for interspinous movement (ISM) (22 of 39, 56.4%) and change in Cobb angle (12 of 39, 30.8%). Computed tomography (CT) based findings (21 of 39, 53.8%) were employed in ambiguous cases with improved sensitivity and specificity. Reconstructed CT scans were used to assess for intragraft bridging bone and extragraft bridging bone (ExGBB). ExGBB were proved to have the highest diagnostic sensitivity and specificity for pseudoarthrosis detection when compared to all other radiographic criteria. The ISM <1 mm on dynamic flexion-extension radiographs had high diagnostic sensitivity and specificity as well. After our reviewing, we recommend using dynamic lateral flexion-extension cervical spine radiographs at 150% magnificationin which the interspinous motion <1 mm and superjacent interspinous motion ≥ 4 mm confirms fusion. In ambiguous cases, we recommend using reconstructed CT scans to evaluate for ExGBB.

Keywords: Anterior cervical spine surgery, Anterior cervical discectomy and fusion, Anterior cervical arthrodesis surgery, Cervical spine fusion, Fusion, Pseudarthrosis

INTRODUCTION

The aim of anterior cervical discectomy and fusion (ACDF) surgery is to provide the patient with adequate decompression and rapid fusion to treat cervical degenerative disease, ultimately reducing symptoms of neck pain, radiculopathy, and myelopathy. Since its introduction in the 1950s, ACDF has a proven track record of high fusion rates.[1] However, pseudoarthrosis and adjacent segment disease are known complications of the procedure that may lead to persistent symptoms requiring further revisions surgery which is complicated by prolonged hospital stay and increased morbidity.[1-4] The true etiology of pseudoarthrosis is difficult to ascertain, but there are known risk factors, which include patient factors and surgical factors such as multilevel fusions, instrumentation choice and bone grafts used for the case.[5-7] The reported fusion rate following anterior cervical spine surgery with fixation is as high as 96%,[8] but the majority of reoperation after the anterior approach was due to pseudoarthorsis.[9] Numerous imaging modalities and diagnostic radiographic criteria to determine the fusion status following ACDF have been described and used in recent literature. However, only a few of these radiographic parameters were rigorously analyzed to validate their accuracy and reliability so far. This inconsistency in reporting pseudoarthrosis following ACDF stems from a lack of established radiographic parameters in the literature. This current study aims to review recent literature over the last decade (2008 to 2018) to evaluate the different imaging modalities and radiographic parameters used in prior works. In this review article, we will summarize the findings of previous studies, review the advantages and disadvantages of frequently employed diagnostic criteria, and present our recommended protocol of fusion status assessment with a case example.

MATERIALS AND METHODS

1. Data Source

This study identified longitudinal studies including randomized controlled trials (RCT), observational case-control studies, and prospective and retrospective cohort studies reporting on the success of spinal fusion and how successful fusion was identified and defined after ACDF. The National Institutes of Health PubMed database was queried using a combination of free and medical subject headings search parameters related to the surgical intervention (e.g., "anterior cervical discectomy and fusion," "ACDF," "cervical arthrodesis") and outcome of interest (e.g., "fusion," "pseudoarthrosis," "nonunion," "treatment outcomes") in major journals. There were no language restrictions on potential studies. Studies that were published within the approximately 10-year period between January 1, 2008 and June 30, 2018 were included for inclusion in this study to assess for recent trends in radiographic pseudoarthrosis diagnosis. Studies without clear radiographic fusion criteria, literature review, case reports, and fusion assessment of upper cervical spine and craniocervical junction were excluded. A list of relevant articles was identified using these search terms by 3 authors (WL, AH, VB) and were manually screened for inclusion in this current review. All longitudinal studies that reported on a cohort of patients who underwent ACDF for any indication and who were followed postoperatively for fusion status were included in this study.

2. Data Extraction

After an initial screen of abstracts and article titles, we obtained full text articles of all potential studies. Three reviewers independently assessed the articles using the inclusion criteria until a consensus was reached. Relevant data identified from each article was the type of study (RCT, case-control, cohort studies), level of evidence, number of patients included in the study, number of intervertebral levels assessed in the study, imaging modality used to assess spinal fusion (e.g., plain films, computed topography [CT], etc.), and how fusion was assessed from imaging (e.g., trabecular bone bridge, motion, etc.).

RESULTS

In total, 39 articles (Table 1) published between January 1, 2008 and June 30, 2018 met our inclusion criteria.[10-49] The various imaging modalities used to assess fusion status in these studies included radiographs (static and dynamic lateral) and CT imaging. No studies were identified that reported cervical spine fusion or pseudoarthrosis based solely on history or physical examination.

1. Radiographic Assessment

The most frequently used radiographic diagnostic criteria for pseudoarthrosis after ACDF was an absence of bridging trabeculae across the fused levels on static radiographs (31 of 39 used this definition, 79%).[10-40] Fusion status was also frequently assessed using dynamic lateral radiographs. Using this imaging technique, authors measured ISM (22 of 39, 56.4%)[10,13,14,16,19-22,25,28,29,31,33-39,41-43] or used the Cobb angle method (12 of 39, 30.8%)[11,15,17,27,32,34,37,42-46] to assess cervical fusion. No consensus was reached regarding the amount of motion for evaluation of cervical fusion on dynamic lateral radiographs. For the interspinous process method, no motion (9 of 22, 40.9%),[13,14,17,21,24,26,29,33,37] under 1 millimeter (mm) (7 of 22, 31.8%),[10,20,28,31,32,41,42] under 2 mm (2 of 22, 9.1%),[12,35] and under 3 mm of motion (4 of 22, 18.2%)[27,30,40,43] between spinous process were all used as cutoff values for a definition of fusion. Using the Cobb angle method, changes of 1 degree (1 of 12, 8.3%),[38] 1.5 degrees (1 of 12, 8.3%),[42] 2 degrees (5 of 12, 41.7%),[19,25,36,44,46] 4 degrees (4 of 12, 25.0%),[11,43,45] and 5 degrees (2 of 12, 16.7%)[27,30] were all used in various studies.

2. CT Assessment

CT scans were the most commonly used advanced imaging modality to assess fusion status (21/39, 53.8%).[10,12,15,16,19,22,26,29,33-38,41,43,45-49] Fusion was identified in these studies by assessing for continuous bridging bone at the cage or graft endplate interface. Pseudoarthrosis was identified as a radiolucent gap across the fused levels. Reconstructed multi-axial CT scans were also compiled to assess for intragraft bone bridging (InGBB) and

Table 1. Literature review of methods and criteria used for determining fusion from 2008 to 2018 study

No.	First author	Journal	Year	Type of study	Level of evidence	No. of patients	No. of inter-vertebral levels	Fusion assessment
1	Buchowski[3]	Spine	2008	Prospective clinical trial	II	14	N/A	R (static AP, lateral flexion/extension): bridging trabeculae visualized, < 1 mm interspinous process motion on lateral flexion/extension CT: bridging trabeculae seen, no bony lucency seen at graft/vertebral body junction MRI: bony bridging from endplate to endplate without signal alteration at the graft/vertebral body junction Surgical exploration
2	Buttermann[41]	Spine J	2008	Prospective but nonrandomized study	II	66	124	R (lateral flexion/extension): < 1 mm of gapping of the spinous process on lateral flexion/extension films CT: used to assess fusion but did not specify fusion criteria on CT
3	Chiang[22]	Spine	2008	Retrospective study	II	56	85	R (lateral flexion/extension): trabecular bone across the interfaces without lucencies between the cage and vertebral endplates CT: bony bridging formation between superior and inferior endplates
4	Fassett[42]	J Neurosurg Spine	2008	Cohort	II	100	512	R (lateral flexion/extension): distance between the spinous processes in flexion and extension was measured manually (< 1 mm considered fused), and by a proprietary Qualitative Motion Software (< 1.5 degrees of angular motion considered fused)
5	Foley[5]	Spine J	2008	A randomized, controlled, prospective multicenter clinical trial	I	323	N/A	R (AP, lateral flexion/extension): greater than or equal to 50% bony bridging through both surfaces of the graft-vertebra interface, no radiolucency at any portion of the graft-vertebra junction, ≤ 4 degrees of motion between adjacent fused vertebrae
6	Oh[33]	Spine	2009	Retrospective study	II	31	62	R (lateral flexion/extension): absence of motion between spinous process on flexion/extension radiographs, absence of any dark halo around iliac bone graft cages, presence of bridging bone anterior or posterior to a cage or iliac bone graft
7	Song[36]	Spine	2009	Retrospective study	II	78	N/A	R (AP, lateral flexion/extension): less than 2 degrees of movement on lateral flexion/extension, presence of bridging trabecular bone between endplates on AP/lateral views, lack of signs of implant failure of the anterior plate system, less than 50% radiolucency in the perimeter surrounding the cage CT: used to assess fusion but did not specify fusion criteria on CT
8	Tomasino[37]	J Neurosurg Spine	2009	Retrospective study	II	30	30	R (AP, lateral flexion/extension): absence of movement during dynamic measurements of spinous process distance on flexion-extension lateral radiographs, presence of bridging bone at the surgical level CT: presence of bridging bone at the surgical level
9	Uribe[35]	Eur Spine J	2009	Retrospective comparative study	II	80	N/A	R (AP, lateral flexion/extension): absence of motion more than 2 mm between spinous process on flexion-extension lateral radiographs, absence of radiolucent gap between the graft and end plate, presence of continuous bridging trabeculae at the graft and end plate junction
10	Lofgren[38]	Eur Spine J	2010	Prospective randomized study	I	80	N/A	R (AP, lateral flexion/extension): presence of bone-bridging or interface lucencies between trabecular material and bone, measuring the differences between the angles of the spinal process of the fused vertebrae at flexion and extension (< 1 degree was "clearly fused") MRI: Used to assess decompression but was not used to determine fusion status

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Table 1. Continued

No.	First author	Journal	Year	Type of study	Level of evidence	No. of patients	No. of intervertebral levels	Fusion assessment
11	Ghiselli[47]	Spine	2011	Prospective study	II	10	24	R (lateral flexion/extension): distance between spinous processes in flexion and extension measured using Qualitative Motion Software CT: presence of bony trabeculae across the fusion level, lack of bony lucency at the graft/vertebral body junction Surgical exploration
12	Guo[12]	Eur Spine J	2011	Retrospective clinical study	II	120	N/A	R (lateral flexion/extension): absence of motion > 2 mm between spinous processes on flexion-extension lateral radiographs, absence of radiolucent gap between the graft and end plate, presence of continuous bridging trabeculae at the graft and end plate junction
13	Lebl[39]	Spine J	2011	Retrospective comparative cohort study	II	29	29	R (lateral flexion/extension): presence of bony bridging across the interbody space
14	Sugawara[40]	spine	2011	Retrospective study	II	105	165	R (lateral flexion/extension): motion of spinous process on flexion-extension radiographs < 3 mm, visible bony bridging between vertebral bodies, absence of halo around the cages CT: sagittal reconstruction images to identify bony bridging
15	Lin[14]	Eur Spine J	2012	Retrospective study	II	120	N/A	R (AP, lateral flexion/extension): no motion across fusion site on flexion/extension radiographs, trabeculae across the fusion site, no lucency across fusion site or around any screw sites CT: sagittal reconstructive images to identify bony bridging
16	Song[15]	Spine	2012	Retrospective clinical study	II	78	122	R (AP, lateral flexion/extension): presence of bridging bone between grafted bone and vertebral bodies, absence of radiolucent defects, Halo sign, or loss of grafted bone, and new bone formation in the exterior portion of cages and a partial or complete loss of radiopaque line at the endplates by sclerotic changes on the bony bridges between the vertebral endplate and grafted bone in the interior portion of the cage
17	Song[13]	Eur Spine J	2012	Retrospective study	II	40	117	R (AP, lateral flexion/extension): absence of motion between spinous process on flexion/extension radiographs, absence of any radiolucent defects or Halo sign around the iliac bone graft or cages, presence of a bridging bone anterior or posterior to a cage or iliac bone graft at the graft-endplate junction
18	Barbagallo[16]	Eur Spine J	2013	Prospective cohort study	II	32	77	R (AP, lateral flexion/extension): no radiolucencies in the graft-endplate area and bridging trabeculae CT: obtained to confirm neural decompression, rule out fracture but not to assess fusion MRI: obtained to document neural decompression but not to assess fusion
19	Chen[17]	Eur Spine J	2013	Prospective, randomized, control study	II	80	240	R (lateral flexion/extension): absence of motion between spinous processes, absence of a radiolucent gap between the graft and endplates, presence of continuous bridging bony trabeculae at the graft-endplate interface
20	Coric[19]	J Neurosurg Spine	2013	Prospective randomized study	II	74	N/A	R (AP, lateral flexion/extension): > 50% trabecular bridging bone, < 2 degrees of motion or less, and no implant loosening
21	Kim[48]	Neurosurgery	2013	prospective randomized study	I	52	N/A	R (AP, lateral flexion/extension): did not specify fusion criteria on plain films CT: bony fusion defined as fused with remodeling and trabeculae present, graft intact, not fully remodeled and incorporated but with no radiolucencies present

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Table 1. Continued

No.	First author	Journal	Year	Type of study	Level of evidence	No. of patients	No. of intervertebral levels	Fusion assessment
22	Song[18]	Spine	2013	Retrospective study developing diagnostic criteria	II	110	254	CT: extragraft bone bridging (ExGBB) and intragraft bone bridging (InGBB). ExGBB was defined as complete cortical bridging at any peripheral margins of the operated disc space outside of the graft, and InGBB was defined as cortical or trabecular bridging within the confines of the graft only Surgical exploration
23	Song[20]	J Bone Joint Surg Am	2014	Retrospective study	II	125	262	R (lateral flexion/extension): interspinous motion < 1 mm, with superjacent interspinous motion < 4 mm on 150% magnified dynamic lateral radiographs Surgical exploration
24	Grasso[23]	Eur Spine J	2015	Prospective comparative study	II	20	N/A	R (AP, lateral flexion/extension): absence of segmental mobility, absence of radiolucencies, absence of bone sclerosis, and evidence of bridging trabecular bone within the fusion area
25	Lau[24]	J Neurosurg Spine	2015	Retrospective study	II	55	145	R (AP, lateral flexion/extension): Absence of radiolucent lines, bridging trabecular bone across the fusion site, no motion between spinous processes, no motion between vertebral bodies
26	Phillips[25]	Spine	2015	Prospective, randomized controlled Trial	II	293	293	R (AP, lateral flexion/extension): evidence of continuous bridging bone between the adjacent endplates of the involved motion segment, radiolucent lines at < 50% of the graft-vertebra interfaces, < 2 degrees of segmental rotation
27	Shi[46]	Spine J	2015	Retrospective comparative study	II	38	114	R (lateral flexion/extension): < 2 degrees of motion on flexion/extension radiographs, absence of a radiolucent gap between the graft and the endplate.
28	Wang[21]	Eur Spine J	2015	Retrospective clinical study	II	63	N/A	R (lateral flexion/extension): absence of motion between the spinous processes on dynamic lateral radiographs, absence of a radiolucent gap between the graft and endplates, presence of continuous bridging bony trabeculae at the graft endplate interface CT: used to assess fusion but did not specify fusion criteria on CT
29	Arnold[27]	Spine	2016	Prospective, randomized, controlled, trial	II	319	N/A	R (AP, lateral flexion/extension): evidence of bridging trabecular bone between the involved motion segments, translational motion < 3 mm and angular motion < 5 degrees CT: trabecular bone formation patterns within the intervertebral disc space or bridging bone formation that crossed the interspace
30	Chen[44]	Eur Spine J	2016	Retrospective study	II	54	162	R (lateral flexion/extension): < 2 degrees of motion on flexion/extension radiographs, no radiolucent gap between graft and endplate CT: no radiolucent gap between graft and endplate
31	Liu[26]	Eur Spine J	2016	Retrospective clinical study	II	60	N/A	R (AP, lateral flexion/extension): absence of motion between spinous processes, absence of radiolucent gap between graft and endplate, presence of continuous bridging boy trabeculae at the graft-endplate interface CT: absence of motion between spinous processes, absence of radiolucent gap between graft and endplate, presence of continuous bridging boy trabeculae at the graft-endplate interface
32	Vanichkachorn[45]	Eur Spine J	2016	Prospective clinical study	II	31	N/A	R (lateral flexion/extension): ≤ 4 degrees of angular motion CT: bridging bone across the adjacent endplates on thin cut CT scans with sagittal and coronal reconstructions

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Table 1. Continued

No.	First author	Journal	Year	Type of study	Level of evidence	No. of patients	No. of intervertebral levels	Fusion assessment
33	Li[29]	Eur Spine J	2017	Retrospective clinical study	II	152	N/A	R (AP, lateral flexion/extension): no motion across the fusion site, trabeculae across the fusion site, no radiolucencies across fusion or screw sites CT: obtained to assess fusion status but did not specify fusion criteria on CT MRI: obtained to assess adjacent segment degenerative changes, not to assess fusion status
34	Arnold[30]	Neurosurgery	2018	Prospective, randomized, controlled, multicenter clinical trial	I	319	N/A	R (AP, lateral flexion/extension): evidence of bridging trabecular bone between the involved motion segments and translational motion < 3 mm and angular motion < 5 degrees CT: trabecular bone formation patterns within the intervertebral disc space or bridging bone formation that crossed the interspace
35	Basques[34]	Eur Spine J	2018	Retrospective cohort study	II	404	N/A	R (AP, lateral): anterior and posterior bone bridging was present
36	Buttermann[28]	Spine	2018	Prospective cohort study	II	159	N/A	R (lateral flexion/extension): continuous trabeculation and no > 1 mm splaying of the tips of the spinous processes of the fused level CT: used to assess fusion but did not specify fusion criteria on CT
37	Feng[43]	Eur Spine J	2018	Prospective randomized controlled study	II	55	90	R (AP, lateral flexion/extension): rotation < 4 degrees and < 1.25 mm translation with the absence of motion adjacent to interspinous processes (> 3 mm) in the flexion/extension view CT: presence of continuous trabecular bone bridging either anterior, posterior, or within the PEEK cage
38	Lee[31]	Spine	2018	Retrospective comparative study	III	89	151	R (lateral flexion/extension): interspinous distance change of < 1 mm on > 150% magnification, presence of bridging bone across the graft into the adjacent endplates and/or bridging bone outside the graft, radiolucent lines extending < 50% from the cortical-host bone interface CT: presence of bridging bone across the graft into the adjacent endplates and/or bridging bone outside the graft, radiolucent lines extending < 50% from the cortical-host bone interface
39	Riew[32]	Spine J	2018	Retrospective radiographic comparative study	II	82	151	R (lateral flexion/extension): interspinous movement < 1 mm at the arthrodesis level and interspinous movement ≥ 4 mm at a non-arthrodesed superjacent level based on 150% magnified dynamic radiographs CT: presence of bridging bone and/or the lack of radiolucency at the graft-vertebral junction, presence of ExGBB and InGBB Surgical exploration

R, radiographs; AP, anteriorposterior; CT, computed tomography; MRI, magnetic resonance imaging; PEEK, polyetheretherketone.

extragraft bone bridging (ExGBB).[18,32]

DISCUSSION

Achieving fusion after ACDF is critical to attain predictable postoperative pain relief and functional recovery. Pseudoarthrosis is an uncommon, but known complication after ACDF that leads to persistent unresolved symptoms, which often requires revision surgeries.[1-4] Although the gold standard to assess pseudoarthrosis is operative exploration of fusion mass, the preoperative radiographic options to determine fusion status is still poorly described in the literature. The pseudoarthrosis rate is affected by patient factors (diabetes, smoking, etc.), fusion levels, graft choice, and surgical instrumentation, but the true etiology remains difficult to establish given high rates of asymptomatic patients and inconsistent diagnostic radiographic parameters.[32,50-53] Therefore, the purpose of this review study was to inspect the articles published over the past decade to assess which imaging modality and radiographic parameters were used to diagnose fusion after ACDF to identify current trends and consensus protocols for radiographical assessment of fusion status.

In this systematic review study of 39 articles published between January 1, 2008 and June 30, 2018, the fusion status after ACDF was confirmed with different imaging modalities in addition to the history and physical exam of the patients. All the studies included cervical spine radiographs as one of the tools used to assess the fusion status and most studies used more than one criterion, which suggests a more stringent criteria for fusion assessment since our previous review article.[53] The use of cervical spine films as a first line to diagnose pseduoarthrosis stems from low costs, easy accessibility, and low radiation for the patient.

Static anteroposterior and lateral cervical spine films are consistently described as the initial approach to assess ACDF postoperative fusion status in recent literature. These films expose the patients to low-dose radiation and provide the clinician with valuable information regarding fusion status. In the static films, fusion is confirmed with formation of osseous bridging between the graft and vertebral body across the fused levels. Pseudoarthrosis is diagnosed with static films when there is an absence of this osseous bridging and a presence of haloing or lucency around the graft.[10,33] However, pseudoarthrosis diagnosed in plain films only correlates between 43%–82% with pseudoarthrosis detected during operative exploration of fusion mass, which is most likely secondary to the inability of films to accurately assess bony morphology with an implant in place.[54] Among the 39 included articles, only two studies determined cervical spine fusion status or pseudoarthrosis based solely on static radiographs as the only modality.[23,40] Given the lower rate of pseudoarthrosis detection using just the static films, the recent trends for pseudoarthorsis diagnosis have moved from relying on static radiographs to dynamic radiographs and advanced imaging. The dynamic lateral flexion-extension cervical spine films provide an improved method of assessing postoperative ACDF fusion status. The dynamic films can either evaluate for the ISM or the change in Cobb angle, both of which have a wide range of diagnostic radiographic parameters in literature. The ISM measurement was much more prevalent in recent works, which accounted for more than half of the literature reviewed in this study. The ISM measurement leading to no movement (40.9%) [13,14,17,21,24,26,29,33,37] and the Cobb angle change of less than 2 degrees (41.7%)[19,25,36,44,46] were the most common method to confirm fusion after ACDF in recent literature. Song et al.[20] evaluated the accuracy of different radiographic parameters used to assess fusion status after ACDF and reported that less than 1 mm of ISM showed the best accuracy and agreement with intraoperative exploration. In this study, he demonstrated increased inter and intraobserver reliability of ISM measurement using magnified 150% radiographs compared to the 25% and 100% magnification, which was observed in future studies as well.[20,31] Another comparative study conducted by Riew et al.[32] demonstrated that < 1 mm ISM cutoff value showed a reliable accuracy compared with conventional CT based bridging bone criteria and showed acceptable sensitivity and specificity second only to ExGBB. Although no motion in ISM is frequently used in recent literature to validate fusion, there is concern that this method may increase the number of reported pseudoarthrosis since micromotion still exists within the solidly fused levels on dynamic films. On the other hand, the cutoff value of less than 2 mm of ISM measurement may overestimate fusion rate, leading to missed diagnosis of pseudoarthrosis. Also, there is no literature confirming the validity of no motion or less than 2 mm of ISM as a reliable method of pseudoarthrosis detection. An important aspect of measuring the ISM is to also be mindful of the superjacent ISM which should be more than 4 mm to increase negative predictive value and sensitivity. Although the no motion of ISM is frequently described in recent literature as a method of pseudoarthrosis diagnosis, only the ISM less than 1mm have been shown to have reliable accuracy.

The dynamic flexion-extension films can also assess for the change in Cobb angle between the adjacent fused vertebrae to

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determine postoperative fusion status. Recent literature frequently employed the change in Cobb angle as a criteria to confirm fusion (30.8%),[11,15,17,27,32,34,37,42-46] but the radiographic parameters ranged from 1.5 to 5 degrees. Cannada et al.[4] showed that changes in Cobb angle of 2 degrees lead to a sensitivity of 82% and specificity of 39%. This significantly improved with the Cobb angle change of 4 degrees that resulted in a specificity of 100%.[4] However, the Cobb angle measurement may be a less reproducible form of radiographic parameter compared to the ISM measurement. The Cobb angle measurement is closely associated with the instantaneous center of rotation while obtaining the dynamic cervical spine films, making an accurate and consistent angle measurement difficult. Although there is evidence that combining quantitative motion analysis software with dynamic radiographs may yield objective and reliable numbers compared to manual or subjective measurements, the limitation of specialized technology and software availability make this less useful.[42,47] The difficulty of consistently reproducing the Cobb angle measurement makes this a less appealing method to diagnose pseudoarthrosis for the authors.

In addition to plain radiographs, CT scans were frequently used (53.8%),[10,12,15,16,19,22,26,29,33-38,41,43,45-49] to assess pseudoarthrosis following ambiguous radiographic findings. The interobserver reliability of predicting pseudoarthrosis is better using the CT scan despite the metal artifacts compared to dynamic cervical spine films.[10] The radiographic parameter for CT scan based fusion diagnosis is still in flux in recent literature. Kim et al defined bony fusion as "fused with remodeling and trabeculae present" or "graft intact, not fully remodeled and incorporated, but no lucency present," which is more of a general vague description of fusion status.[48] Other CT scan based parameters used the lack of motion in fused segments and at times no specific parameter was described for fusion assessment.[14,28,29,37,47,55] Song et al.[18] first described the ExGBB and InGBB on CT scans to subcategorize the areas of achieved fusion in 2013. Riew et al.[32] further evaluated the ExGBB and InGBB in multiaxial reconstructed CT scans and reported that ExGBB had the highest sensitivity and specificity and acceptable accuracy to detect pseudoarthrosis, but InGBB was worse than guessing. Although the CT scan is superior to standard films in evaluating bony fusion status, it is limited to findings derived from a static moment in time. It fails to assess for dynamic changes in the cervical spine during motion, which may leave out some cases of pseudoarthrosis seen only with movement. Also, the CT scan based fusion status is based on subjective interpretation compared to the objective measurement findings on standard films, which make the results more vulnerable to both type I and type II errors.[47] In addition, because of the imaging features of cortical allografts, the CT evaluation may actually omit the nonunion and overstate the fusion rates, particularly during the early post-

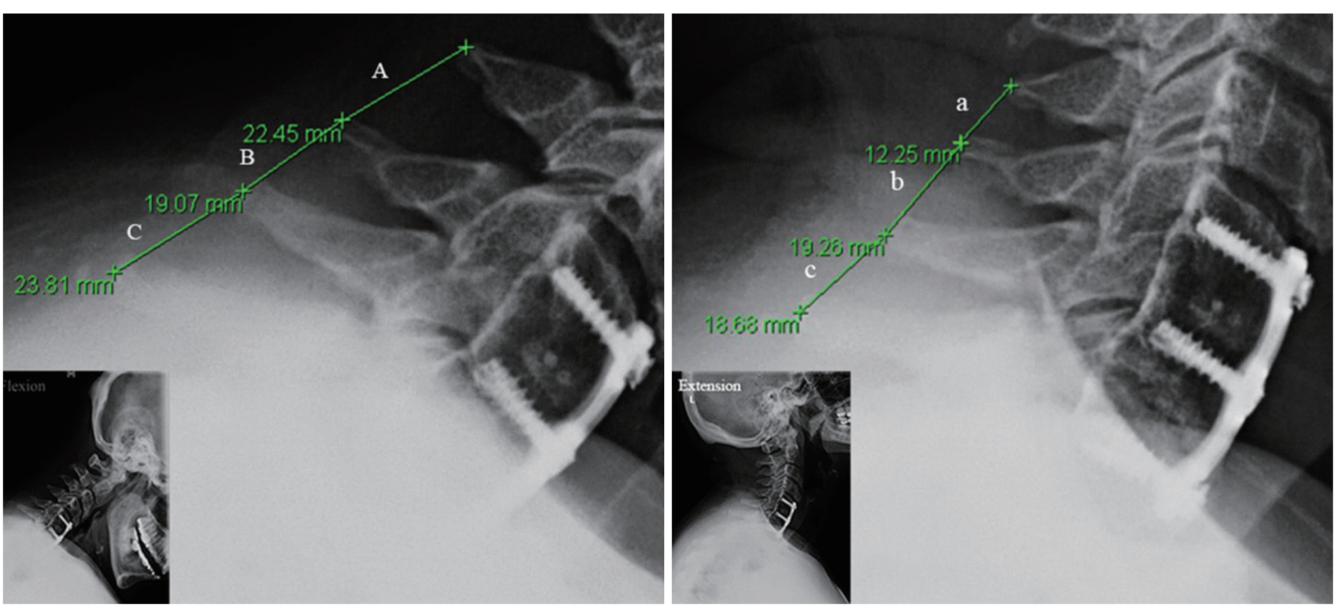

Fig. 1. Measurement of interspinous movement (ISM) at superjacent level (C4–5) and operated levels (C5–7) on the 150% magnified flexion and extension radiographs. The superjacent ISM at C4–5 (A and a) is 10.2 mm, which indicates adequate dynamic motion (>4 mm). ISM at C5–6 (B and b) is 0.21 mm, which is consistent with our definition of fusion (<1 mm). ISM at C6–7 (C and c) is 5.13 mm, which indicates pseudoarthrosis (>1 mm).

operative follow-up period. The published CT based pseudoarthrosis diagnosis is inconsistent with other radiographic nonunion indicators including internal fixation failure, peri-instrument halo signs, and cystic changes around the grafts.[20] Overall, the CT scan is a valuable tool used to confirm equivocal findings on standard radiographs given its improved pseudoarthro-

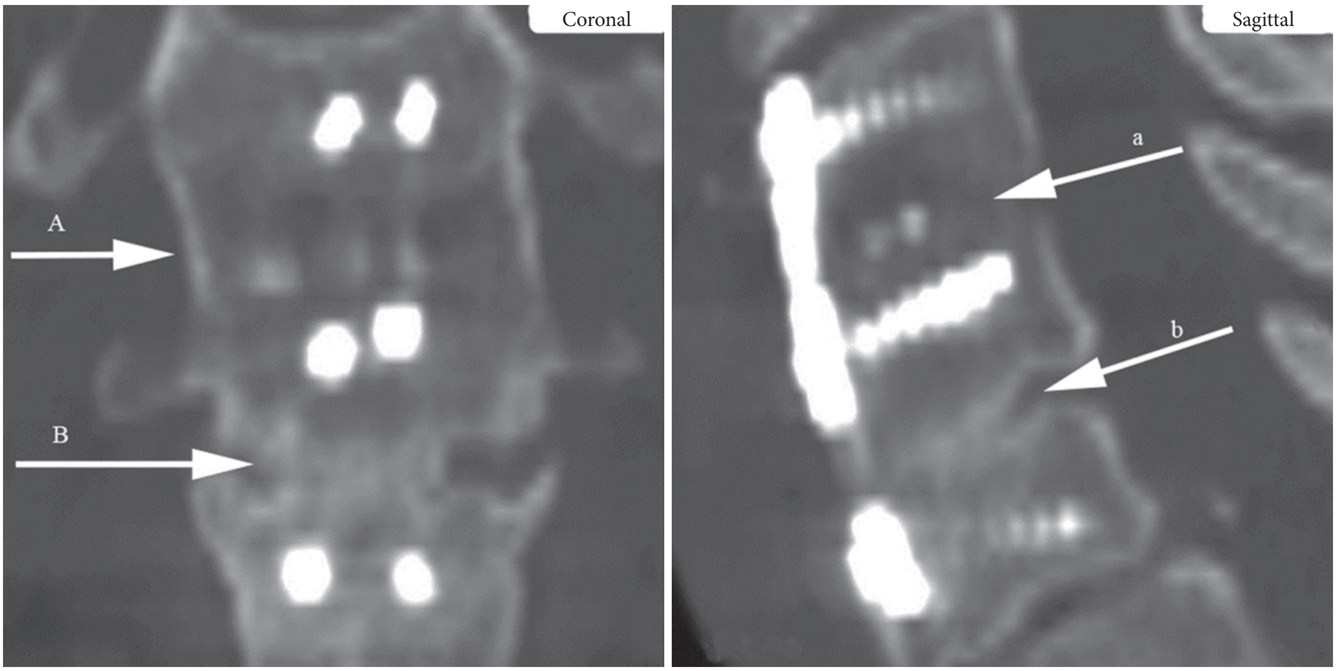

Fig. 2. Evaluating bone bridging on multiaxial reconstructed coronal and sagittal computed tomographic images. It appears to be fused with bone bridging formation at both C5–6 (A and a) and C6–7 (B and b) levels.

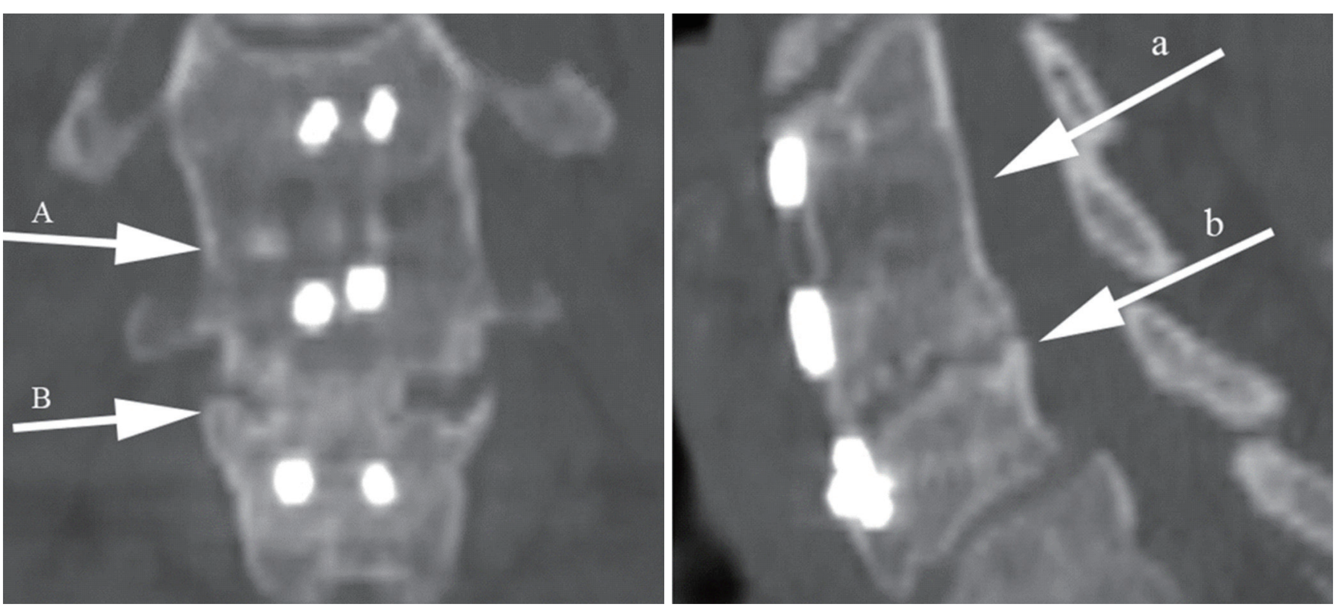

Fig. 3. Evaluating extragraft bridging bone (ExGBB) on multiaxial reconstructed coronal and sagittal computed tomographic images. The top level (C5–6) shows ExGBB on both the coronal and sagittal images (A and a). The bottom level (C6–7) shows intragraft bone bridging on the coronal view (B) but demonstrates a cleft and no ExGBB on sagittal image (b), which indicates pseudoarthrosis. This is consistent with the results of interspinous movement evaluation on X-rays and was confirmed to be pseudoarthrosis with intraoperative exploration.

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sis detection rate, but care must be taken prior to obtaining the imaging given its limitations.

CONCLUSION

Diagnosing pseduoarthrosis after ACDF is controversial and the literature is inconsistent in objectively evaluating postoperative radiographic findings. After reviewing the recent studies, we find that no one single method is absolutely perfect for the diagnosis of pseudoarthrosis. After taking the advantages and disadvantages into consideration, we recommend first using the dynamic lateral flexion-extension cervical spine films in 150% magnification as the initial method for evaluation, since this is economically prudent, quick, and most informative of dynamic cervical spine movements with low radiation for the patient. The interspinous motion < 1 mm and superjacent interspinous motion ≥ 4 mm confirms the fusion diagnosis in the dynamic films (Fig. 1). In ambiguous cases (Fig. 2), we recommend using the reconstructed multiaxial CT scans to evaluate for ExGBB given its superior diagnostic qualities (Fig. 3).

CONFLICT OF INTEREST

The authors have nothing to disclose.

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