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Dynamic Radiographic Criteria for Detecting Pseudarthrosis Following Anterior Cervical Arthrodesis

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Background: While interspinous motion analysis is commonly used to determine the status of an anterior cervical fusion, the accuracy of this technique is unclear. We believed that three questions needed to be answered. What degree of image magnification is ideal? How much motion should be considered ''adequate'' for making dynamic radiographs? What is the optimal amount of interspinous motion for detecting pseudarthrosis?

Methods: We performed a retrospective study of 125 patients (109 fused segments and 153 pseudarthrotic segments) who had undergone reexploration with confirmation of fusion status. Interspinous motion at each operatively treated level and one superjacent level was measured by two independent investigators twice. Reliabilities of interspinous motion analysis at different magnification rates (25%, 100%, 150%, and 200%) were evaluated for fifty randomly selected segments to determine the optimal magnification, which we used for the remainder of the measurements. Fusion status was also determined on computed tomography (CT) by two other raters. We compared the intraoperative findings with those based on dynamic radiographs (with use of cutoff values of 1 and 2 mm of interspinous motion as the indication of pseudarthrosis) and CT.

Results: On radiographs, both 150% and 200% magnification yielded higher interobserver and intraobserver reliabilities compared with 25% and 100% magnification, and the reliabilities at 150% and 200% were similar to each other, so subsequent measurements were made at 150%. The cutoff value of interspinous motion for detecting pseudarthrosis was 0.9 mm as determined with receiver operating characteristic curve analysis. Compared with CT, interspinous motion of ≥1 mm showed relatively low sensitivity (79.5%) and negative predictive value (77.1%) and similar specificity (97.0%) and positive predictive value (97.4%). Using interspinous motion of ≥2 mm as the cutoff decreased the sensitivity and negative predictive value to 46.6% and 56.8%, respectively. Our evaluation of what constituted adequate dynamic motion for making the radiographs showed that, with use of interspinous motion of ≥1 mm as the cutoff for detecting pseudarthrosis, superjacent interspinous motion of ≥4 mm increased the sensitivity and negative predictive value (86.3% and 83.4%) compared with those associated with alternative cutoffs of superjacent interspinous motion (≥3.5, ≥5, and ≥6 mm), and the specificity (96.1%) and positive predictive value (96.9%) were reasonable.

Conclusions: Use of interspinous motion of ≥1 mm as the cutoff for detection of anterior cervical pseudarthrosis on radiographs magnified 150% and made with superjacent interspinous motion of ≥4 mm yielded accuracies comparable with those of CT.

Level of Evidence: Diagnostic Level II. See Instructions for Authors for a complete description of levels of evidence.

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Diagnosis of symptomatic pseudarthrosis following anterior cervical fusion can be based on clinical presentation and radiographic images after other causes of persistent pain have been excluded. However, some patients with pseudarthrosis may have minor or no symptoms, and we are aware of no diagnostic radiographic tool with 100% accuracy[1-4]. As fusion rates may be overestimated, clinical suspicion is important for detecting pseudarthrosis[3,5].

Surgical exploration generally remains the standard method for defining fusion status[1,6-8]; however, careful exploration is necessary, especially anteriorly, as there may be a thin veneer of what appears to be contiguous bone overlying a pseudarthrosis. Among various radiographic tools, computed tomography (CT) has been commonly considered the most reliable radiographic modality to assess fusion status[1-3,6]. Static radiographs have not been useful for determining fusion status, but dynamic flexion-extension radiographs traditionally have been widely used for assessing motion because the modality is easy to reproduce, is affordable in clinical settings, and is a reasonable screening tool to detect pseudarthrosis[1,3,9]. Unfortunately, the measurement of motion on dynamic radiographs can be inaccurate and affected by the voluntary effort of the patient[10-12], giving rise to questions regarding the amount of motion on dynamic radiographs that is compatible with pseudarthrosis[1,3]. Many reports[11-18] have described radiographic parameters indistinctly, including the degree of magnification used and how it was determined whether the dynamic motion on radiographs was inadequate. Furthermore, only a few authors[6,10,15] have related their criteria to surgical confirmation of anterior cervical fusion status.

The purpose of the current study was to determine the amount of interspinous motion on dynamic cervical radiographs that correlates with a solid fusion as seen on CT scans and at surgical exploration following anterior cervical arthrodesis. We thought three questions needed to be answered regarding interspinous motion analysis as a diagnostic test: (1) What degree of image magnification is ideal for detecting interspinous motion on dynamic radiographs? (2) How much motion is required for a dynamic radiograph to be considered "adequate"? (3) What is the optimal interspinous motion for accurately diagnosing pseudarthrosis at each cervical level?

Materials and Methods

Subjects

This study was a retrospective radiographic investigation approved by the hospital institutional review board. We searched the records from December 2011 back to January 2004 for patients who had been operated on consecutively through an anterior or posterior approach by the senior author (K.D.R.) at a single tertiary academic medical center for reasons such as pseudarthrosis or adjacent segment pathology following previous anterior arthrodesis of any levels from C3-C4 to C7-T1. All patients had to have had the index anterior cervical arthrodesis at least one year before the time of the study. They also had to have had dynamic flexion-extension radiographs and a CT scan made just prior to the revision operation and stored on our Picture Archiving and Communication System (PACS; Siemens Magic Software, Munich, Germany; precision of 0.1 mm). Exclusion criteria were vertebral levels with concomitant posterior operations of any kind, corpectomy at two levels or more, uncertain fusion status during operative exploration, and a pathologic, infectious, or traumatic condition. The medical records were reviewed for diagnosis, and the results of surgical exploration for fusion status were reviewed as well. Demographic data included age at revision surgery, sex, surgery levels, superjacent level (just above the level of the fused segment[s]), and type of revision surgery (Table I).

Radiographic Evaluation

The difference (in millimeters) in the interspinous process distance between the flexion and extension cervical radiographs was used to measure interspinous motion at each cervical level. The most identifiable landmark around the tip of the spinous process at each level was employed. The chosen landmark must be identifiable on both flexion and extension views simultaneously on the same monitor (Fig. 1). In the nineteen cases with a previous one-level corpectomy, interspinous motions at each cervical level were measured. To establish the ideal magnification for fusion assessment, we evaluated the differences in

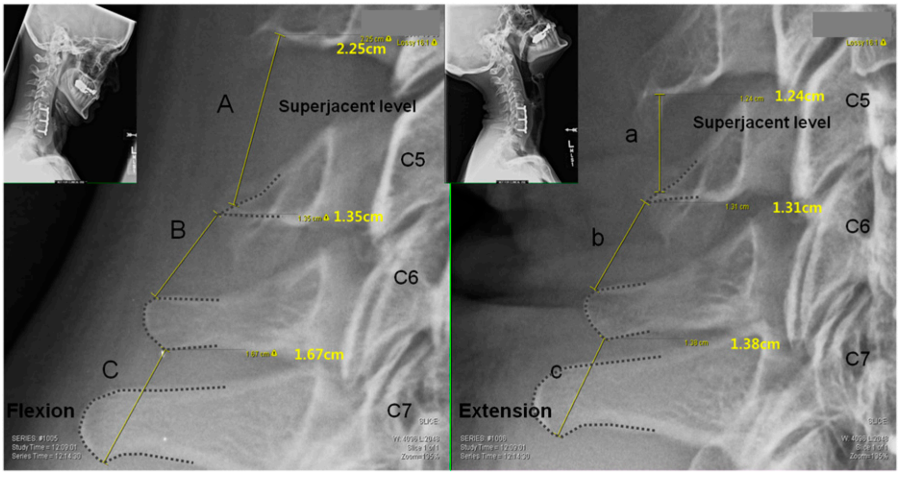

Fig. 1

The measurement of interspinous motion at each surgical level (C5-C6 and C6-C7) and the superjacent level (C4-C5) on dynamic radiographs. Interspinous motion at C5-C6 is 0.4 mm (B and b), interspinous motion at C6-C7 is 2.9 mm (C and c), and superjacent interspinous motion at C4-C5 is 10.1 mm (A and a). The radiographs were magnified 150% as compared with the images on the upper left, and the magnification rate can blind the measurer regarding anterior operative levels on a computer monitor with a diagonal length of 48.3 cm showing flexion and extension radiographs simultaneously.

TABLE I Demographic Data

	Fused Segments (77 Patients, 109 Segments)	Pseudarthrotic Segments (107 Patients, 153 Segments)
Mean age (95% CI) at revision surgery *(yr)*	52.68 (51.18-54.18)	51.05 (49.45-53.65)
Male:female ratio *(no. of segments)*	41:68	66:87
No. of surgery levels (C3-C4/C4-C5/C5-C6/C6-C7/C7-T1)	10/25/47/23/4	11/24/58/55/5
No. of superjacent levels* (C2-C3/C3-C4/C4-C5/C5-C6)	34/37/32/6	32/47/64/10
No. with anterior revision surgery	44 segments in 35 patients	52 segments in 43 patients
No. with posterior revision surgery	65 segments in 42 patients	101 segments in 64 patients
No. with anterior/posterior revision surgery due to adjacent segment pathology	20 segments in 14 patients/10 segments in 6 patients	

*Just above the level of the operatively treated segment(s).

interobserver and intraobserver reliabilities of interspinous motion measurement among four magnification rates (25%, 50%, 150%, and 200%) at fifty randomly selected levels. We then used the selected magnification rate to determine the interspinous motions for each of the 262 segments. All measurements were independently performed on a computer monitor with a diagonal length of 48.3 cm, showing flexion and extension views simultaneously, with use of PACS. Radiographic measurements were performed by two experienced, independent spine surgeons (C.P. and K.-S.S.) at two different time points, separated by three weeks. The interspinous motion at the level superjacent to the fused segment(s) was measured in the same manner at the time of the second measurement and expressed as the average of the measurements made by the two surgeons (Fig. 1). The superjacent interspinous motion was used to determine if a set of dynamic flexion-extension radiographs demonstrated adequate motion. All patients were instructed to maximally flex the neck (chin to chest) and then extend it (face toward ceiling) for the radiographs, and the distance between the tube and target was 182 cm. CT scans were evaluated by two independent spine surgeons (M.S.P. and T.C.) on two occasions separated by a three-week interval. Nonunion was defined as no bridging bone and/or the presence of radiolucency at the graft-vertebral junction. The reliabilities of the interspinous motion analysis and CT scans were assessed for all measurement values. For interspinous motion, a receiver operating characteristic curve was calculated to estimate the ideal cutoff value for detection of pseudarthrosis, and we evaluated the intraoperative findings, currently debated cutoffs for detection of pseudarthrosis (interspinous motion of ≥1 mm and interspinous motion of ≥2 mm), and CT scans.

Exploration of Fusion

All surgical explorations were performed by the senior author (K.D.R.). In the case of anterior exploration, fusion status was confirmed with use of the techniques described below after removal of the anterior plate, if there was one in place. The presence of black titanium metal debris was taken as evidence, although inconclusive, of nonunion. Screws that had a very tight purchase above and below the segment were also inconclusive evidence of a solid fusion, whereas a loose screw was associated with a pseudarthrosis. However, the ultimate determination of fusion status was made with high-powered microscope inspection of the fusion mass, which required removal of all soft tissues and inspection for any fissures in the bone by burring off 1 to 2 mm of the ventral cortical bone. If the fusion status was still in doubt after this had been done, we placed distractor pins (Caspar Cervical Distractor/Compressor; Biomet, Warsaw, Indiana) cranial and caudal to the cleft and performed distraction and compression while we looked for any motion. Posteriorly, we inspected the facet joints using the highest-power microscope visualization while prying the spinous processes apart with a small Cobb elevator. Solid fusion was evidenced by bridging bone overlying either facet (mature fusion) or when the facet joints had no motion. Pseudarthrosis was indicated by obvious motion of the facet joints with the same maneuver. In some instances, the fusion status was indeterminate when the above techniques were used because there was equivocal motion of one or both joints. In such cases, these levels were designated "indeterminable" and were not included in our study.

Statistical Analysis

To estimate the sample size, we referenced a recent study[10] suggesting that the area under the curve for cervical segmental angles determined with use of quantitative motion analysis software to detect anterior cervical pseudarthrosis was 0.85. We wanted the area under the curve for interspinous motion to be 0.90. With $\alpha = 0.05$, one-tailed, and a power of 80%, the allocation ratio of the pseudarthrosis and fusion groups was 3:2. We needed 138 levels in the pseudarthrosis group and ninety-two levels in the fusion group. Considering an exclusion rate of 9%, 150 levels in the pseudarthrosis group and 100 levels in the fusion group were required.

The normal distribution of the collected data was first evaluated with use of the Shapiro-Wilk test. As interspinous motion measurements were abnormally distributed, intraobserver and interobserver reliabilities of the agreement with regard to each measurement were assessed with use of Spearman correlation for interspinous motion measurements and with use of Cohen kappa statistics for CT evaluation. Additionally, we used a Bland-Altman plot analysis of inter-individual difference against the average of the two observers for interspinous motion. Two limits of agreement (mean and ± 1.96 standard deviation [SD]) plots were combined on the graph. Null hypotheses of no difference were rejected if p values were <0.05.

Source of Funding

There was no external funding for this study.

Results

Two hundred and sixty-two levels (109 fused and 153 pseudarthrotic) in 125 patients were analyzed according to the sample-size calculation. The reasons for the revision operations were suspected symptomatic pseudarthrosis (105 patients) or clinical adjacent-segment pathology (twenty patients).

Reliability According to Magnification Rates (see Appendix)

Intraobserver and interobserver reliabilities tended to improve with larger magnification. The intraobserver reliabilities of the two measurers at 150% and 200% magnification ranged from

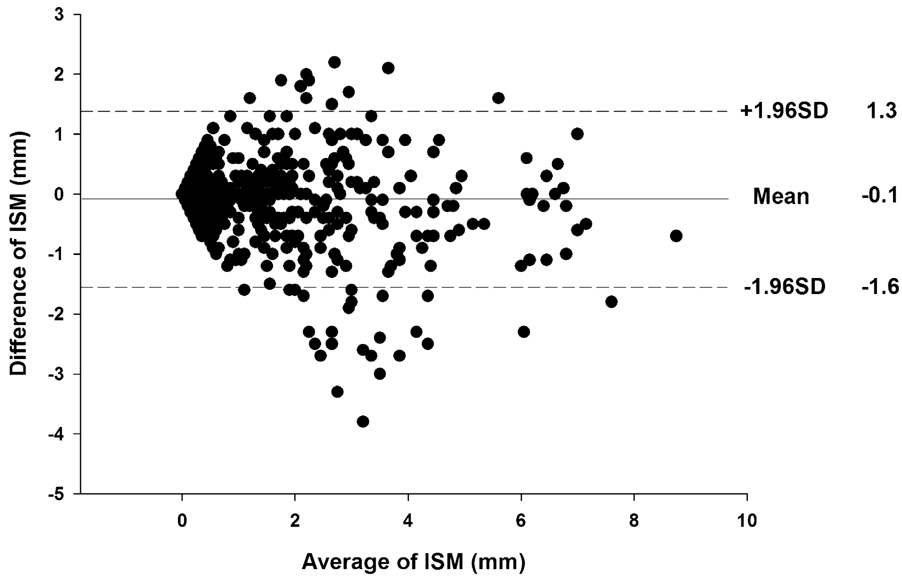

Fig. 2
Bland-Altman scatter plots for differences in interspinous motion (ISM) measurements between the two measurers.

0.749 to 0.918, compared with a range of 0.472 to 0.645 at 25% and 100% magnification. The interobserver reliabilities were 0.796 at 150% and 0.793 at 200% compared with 0.447 at 25% and 0.529 at 100%. Therefore, we arbitrarily decided to utilize 150% magnification for all subsequent interspinous motion measurements.

Accuracy of Interspinous Motion Analysis and CT Evaluation

To illustrate the limits of interobserver agreement, we plotted the Bland-Altman scatter plots for interspinous motion (Fig. 2). The 95% limit of interobserver difference ranged from −1.6 to 1.3 mm. The average interobserver difference was −0.1 mm, indicating no systematic differences between observers. A few numbers of the plot fell outside the limits of agreement, and for all measurements the mean differences were not associated with the means of interobserver measurement, confirming an acceptable level of interobserver agreement.

The intraobserver reliabilities (Spearman correlation coefficients) for interspinous motion measurement were 0.852 (95% confidence interval [CI]: 0.815 to 0.882) and 0.877 (95% CI: 0.846 to 0.902). The interobserver reliability of the two measurers was 0.825 (95% CI: 0.782 to 0.862). The intraobserver reliabilities (kappa values) for the CT scans were 0.900 (95% CI: 0.847 to 0.953) and 0.816 (95% CI: 0.746 to 0.888), and the interobserver reliability was 0.801 (95% CI: 0.738 to 0.864).

Amount of Interspinous Motion with a Pseudarthrosis

The cutoff value for the interspinous motion indicating an anterior cervical pseudarthrosis was 0.9 mm as determined from the receiver operating characteristic curve, and the area under the curve was 0.899 (see Appendix). With use of the criterion of interspinous motion of ≥1 mm to detect anterior cervical pseudarthrosis, the sensitivity and negative predictive value were 79.5% and 77.1%, lower than the respective values of 87.2% and 84.4% for the CT scan. However, the specificity and positive predictive value were 97.0% and 97.4%, comparable with 97.4% and 97.9% for the CT scans. When interspinous motion of ≥2 mm was used as the criterion, the sensitivity and negative predictive value decreased to 46.5% and 56.8% without significant improvement in the specificity or positive predictive value (see Appendix).

Effects of Superjacent Interspinous Motion on Validity of Interspinous Motion Measurements

With regard to how much motion was necessary at the superjacent level for an adequate dynamic radiograph, the sensitivity and negative predictive value increased until superjacent interspinous motion was ≥4 mm and decreased when the criterion for superjacent interspinous motion was ≥5 and ≥6 mm. Thus, <4 mm of superjacent interspinous motion was presumed to be inadequate dynamic motion. Use of the criteria of ≥4 mm of superjacent interspinous motion and ≥1 mm of interspinous motion yielded the highest sensitivity (86.3%) and negative predictive value (83.4%), values comparable with those of a CT scan (87.2% and 84.4%, respectively) (see Appendix).

Discussion

In many studies[16,17,19-22], the authors defined anterior cervical fusion status using only motion analysis and/or radiographic findings. However, we are aware of no standardized motion criteria for pseudarthrosis that include both the segmental angle and the interspinous distance; the criteria range from no motion to a 4° segmental angle and range from absent motion to 2 mm of interspinous motion[1-3]. This lack of a common definition of abnormal sustained motion makes comparison of published fusion rates difficult and interobserver reliability poor. Furthermore, a few studies[6,10,15] have provided the validity

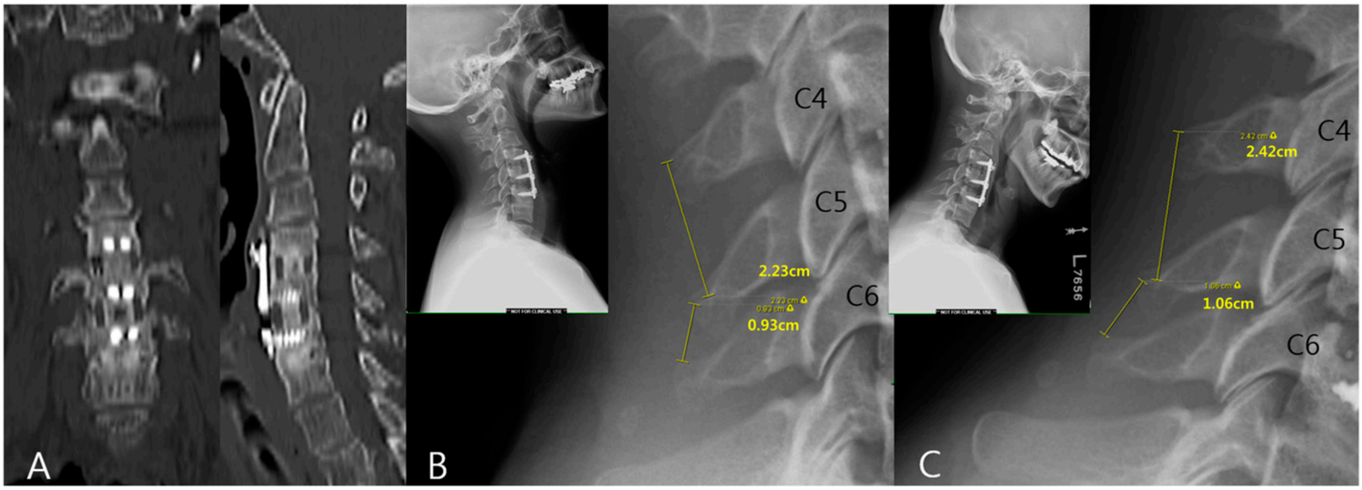

Fig. 3

CT scans (**Fig. 3-A**) showing bridging bone at C4-C5 and bridging bone with a suspicious lucent line at C5-C6. However, interspinous motion analysis (**Fig. 3-B** [extension view] and **Fig. 3-C** [flexion view]) at C4-C5 and C5-C6 showed 1.9 and 1.3 mm of motion, respectively, and pseudarthrosis at these two levels was surgically confirmed.

of motion analysis as related to surgical confirmation, but the cohort sizes were underpowered to demonstrate its validity as a diagnostic test.

Theoretically, it may be easier to obtain evidence of sustained motion by assessing interspinous distance than by obtaining angle measurements because the instantaneous center of rotation[23] is located near the superior aspect of the inferior vertebral body in the sagittal plane. Spinous process tips are located farther from the center of rotation than are the apices of vertebral bodies used in angle measurements, and angle measurement usually requires four points, which could be easily influenced by degenerative change, whereas measurement of interspinous distance requires just two points (see Appendix). The above theoretical advantages of interspinous motion analysis were noted in another study[15] as well.

We asked three questions to evaluate interspinous motion as a diagnostic predictor of anterior cervical pseudarthrosis. First, does the measurement accuracy vary with the magnification? We are aware of no study evaluating motion analysis in which the details of magnification were reported, even though appropriate magnification could be an important factor for accuracy. In our comparisons of reliability coefficients according to different magnification rates, we came to a consensus that a magnification rate of at least 150% can provide better reliability. Various methods have been used to eliminate the subjectivity generally associated with measurements on radiographs—for example, use of quantitative motion analysis (QMA) software[10,11,13] and even a radiostereometric method[12] in vivo for biplanar radiographs. A recently published study[10] investigating criteria for measuring the segmental angle with use of QMA showed the value for the area under the curve to be 0.85, in comparison with 0.899 in our study. With a 150% magnification rate, the reliabilities of interspinous motion measurement with use of PACS showed satisfactory correlation coefficients, with all values ≥0.8, and no systemic differences and unbiased measurement between two observers in the Bland-Altman analysis. Therefore, a magnification rate of at least 150% could be an important factor to increase accuracy of interspinous motion measurement on radiographs.

Our second goal was to evaluate what constitutes adequate dynamic motion on flexion and extension cervical radiographs. Superjacent interspinous motion was used to determine the adequate dynamic motion. Basically, interspinous motion analysis to predict pseudarthrosis provided higher specificity and positive predictive values, >95% in all phases of our study, than sensitivity and negative predictive values. Superjacent interspinous motion analysis could be helpful to increase the sensitivity and negative predictive value. The sensitivity and negative predictive value increased from 79.5% and 77.1% to 86.3% and 83.4%, respectively, when superjacent interspinous motion was ≥4 mm. This sensitivity and negative predictive value were comparable with those of the CT scans (see Appendix). Although CT is the most reliable single imaging tool to detect pseudarthrosis, the primary role of CT is to provide additional information to define fusion, not confirm it with 100% accuracy[3]. Sometimes a combination of motion analysis on radiographs and CT is better than using only CT (Fig. 3)[1,3,10]. The criterion of superjacent interspinous motion of ≥4 mm could not be an absolute value because there could be differences in the normal range of motion at individual superjacent levels. Nevertheless, our findings suggest that adequate motion on dynamic radiographs is necessary to increase sensitivity and negative predictive values of interspinous motion analysis to predict pseudarthrosis.

Finally, we evaluated what distance (in millimeters) of interspinous motion is optimal to accurately diagnose anterior cervical pseudarthrosis. Considering the 0.9-mm cutoff value derived from the receiver operating characteristic curve and the fact that the sensitivity and negative predictive value decreased to

46.6% and 56.8% with use of ≥2 mm of interspinous motion as the criterion, as compared with 79.5% and 77.1% when the criterion was ≥1 mm (see Appendix), it appears that interspinous motion of ≥1 mm is a more appropriate diagnostic criterion clinically. This suggests that authors of studies[1,7,15-18,24] using the cutoff value of 2 mm of interspinous motion have overestimated their fusion rate and could have missed the pseudarthrosis cases that had interspinous motions ranging from 1 to 2 mm. Some laboratory studies[10,13,25] have also suggested an inherent inaccuracy of interspinous motion analysis because, even with solid fusion, some motion can occur between spinous processes due to elastic deformation of bone and facet joints. If that were true, interspinous motion analysis as a diagnostic test to detect pseudarthrosis would have a higher false-positive rate. However, our clinical results showed a 3% false-positive rate and a 96.9% positive predictive value (see Appendix).

We found that ≥2 mm of interspinous motion was an inappropriate criterion for diagnosing pseudarthrosis following anterior cervical fusion surgery because the sensitivity is too low. Therefore, we believe that interspinous motion of ≥1 mm should be used as the criterion to predict pseudarthrosis on dynamic lateral cervical spine radiographs. With use of that criterion on dynamic radiographs magnified 150% and on which the superjacent interspinous motion is ≥4 mm can provide higher validities, comparable with those of CT scans. Our conclusions are strengthened by the fact that this study included a large number of anterior cervical fusion segments (262), with CT and intraoperative exploration used for confirmation. We recommend that future investigators using interspinous motion on dynamic cervical spine radiographs to predict anterior fusion status employ these criteria to improve the accuracy of the diagnosis of pseudarthrosis.

Appendix

eA Tables showing intraobserver and interobserver reliabilities according to different magnification rates and performance characteristics according to different amounts of superjacent intersegmental motion as well as figures demonstrating the receiver operating characteristic curve for interspinous motion measurements and schematic drawings of cervical flexion and extension are available with the online version of this article as a data supplement at jbjs.org. ■

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