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# Predictors of Persistent Nonunion Following Anterior Cervical Discectomy and Fusion: A 5-Year Longitudinal Analysis

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# Abstract

### Purpose

To identify independent predictors of persistent nonunion at 5 years in patients with radiographic nonunion 2 years after anterior cervical discectomy and fusion (ACDF), and to derive radiographic risk factors and thresholds for early surgical decision-making.

### Methods

Retrospective cohort of 58 patients who underwent one- to three-level ACDF between 2007 and 2020, had radiographic nonunion at 2 years, and completed 5-year follow-up. Union (n=18) and persistent nonunion (n=40) groups were defined by 5-year fusion status. Preoperative variables (C2–7 sagittal vertical axis, T1 slope, global and segmental cervical motion) and 1-year variables (interspinous motion [ISM], graft bone bridging [GBB], allograft morphology) were compared. Variables significant on univariable analysis underwent a prespecified stability assessment before multivariable Firth penalized logistic regression. Receiver operating characteristic analysis determined optimal cutoffs.

### Results

Persistent nonunion occurred in 69.0% (40/58). Preoperative segmental motion (odds ratio [OR] 1.176; 95% CI 1.041–1.451; P = 0.006) and 1-year ISM (OR 2.329; 95% CI 1.391–4.593; P = 0.001) independently predicted persistent nonunion, whereas any GBB was protective (OR 0.084; 95% CI 0.010–0.425; P = 0.002). Unfavorable allograft morphology was significant on univariable analysis (OR 6.296; 95% CI 1.978–22.559; P = 0.002) but failed the stability criterion (exploratory). Optimal cutoffs were 10.05° for segmental motion (sensitivity 67.5%, specificity 66.7%) and 3.62 mm for 1-year ISM (sensitivity 80.0%, specificity 83.3%).

### Conclusion

Preoperative segmental motion >10.05°, 1-year ISM >3.62 mm, and absent GBB independently predict persistent nonunion 5 years after ACDF. Patients with these findings rarely achieve spontaneous union and are candidates for early revision rather than continued observation.


# Introduction

Anterior cervical discectomy and fusion (ACDF) is one of the most widely performed procedures for cervical radiculopathy and myelopathy. Although ACDF achieves a high fusion rate, nonunion remains a clinically significant complication, occurring in 2.6% to 15.2% of single-level procedures and up to 60% of multilevel constructs [1–3].

Defining the natural history of nonunion after ACDF is essential for appropriate postoperative management. Approximately 72% of nonunion at 1 year achieve fusion by 2 years [4], whereas only

32.6% of those persisting at 2 years fuse by 5 years, with significant worsening of arm pain visual analogue scale (VAS) and neck disability index (NDI) relative to patients with union [5]. These findings indicate that 2-year nonunion is a distinct clinical entity with diminished union potential and a higher risk of symptom deterioration.

Despite these longitudinal observations, no prior study has identified predictors of nonunion that persists to 5 years in patients who have already failed to fuse at 2 years. Early postoperative radiographic parameters—including graft bone bridging (GBB) and dynamic interspinous motion (ISM) at 1 year—have not been evaluated as predictors of long-term fusion failure. Choi et al. [6] reported that greater T1 sagittal slope, lower fusion level, and preoperative segmental cervical motion greater than 12° predict pseudarthrosis at 2 years after ACDF. Park et al. [7] proposed a 4-mm cutoff at 6 months postoperatively as a risk factor for nonunion at 24 months. Whether these parameters predict persistent nonunion at 5 years in patients with established 2-year failure remains unknown.

This study aimed to identify independent preoperative and 1-year postoperative predictors of persistent nonunion at 5 years in patients with confirmed 2-year nonunion after ACDF, and to derive radiographic thresholds for risk stratification and timely surgical decision-making.

## Materials and methods

# Hypothesis

We hypothesized that larger C2–7 sagittal vertical axis (C2–7 SVA), T1 slope, greater global and segmental motion, greater 1-year ISM, and unfavorable allograft morphology increase the risk of persistent nonunion, whereas presence of GBB is protective.

## Study design

The Institutional Review Board of the participating institution approved this retrospective cohort study (IRB No. [blinded for review]) and waived informed consent given its retrospective design. We designed and reported the study in compliance with the Strengthening the Reporting of Observational Studies in Epidemiology (STROBE) statement for cohort studies.

## Study population

We retrospectively reviewed consecutive patients who underwent ACDF for degenerative cervical myelopathy, myeloradiculopathy, or radiculopathy between January 2007 and December 2020. Inclusion criteria were (1) ACDF performed at one to three levels; (2) radiographic nonunion confirmed at 2-year follow-up; and (3) a minimum 5-year follow-up. Exclusion criteria were (1) surgery for infection, tumor, or trauma; (2) prior cervical spine surgery; and (3) combined posterior fusion.

During the study period, 1,077 patients underwent ACDF, of whom 337 completed a minimum 5-year follow-up. Among these, 173 demonstrated radiographic pseudarthrosis at 1 year, and 58 had persistent nonunion at 2 years and constituted the study cohort (Fig. 1).

## Surgical procedure

A single approach was used for all procedures: the standard left-sided Smith-Robinson exposure. After exposure, discectomy and endplate preparation were performed at the indicated levels. A freeze-dried cortical ring allograft (Bone Bank Allografts, San Antonio, TX) filled with local bone harvested during spur removal was then impacted into the disc space. We minimally decorticated the superior and inferior endplates while preserving cortical bone to prevent subsidence and sized the graft at least 2 mm greater than the original disc height [8]. All levels were instrumented with an anterior cervical plate and variable angle screw constructs with integrated locking technology. A Miami J collar was worn for 6 to 12 weeks.

## Assessment of pseudarthrosis and nonunion

Cervical dynamic radiographs were performed preoperatively and during each postoperative visit. Computed tomography (CT) was routinely performed at 1 and 2 years after surgery to assess fusion. For patients diagnosed with nonunion at 2 years, a follow-up CT scan was obtained at 5 years.

Nonunion was defined using previously validated criteria: (1) interspinous motion > 1 mm on ≥ 150% magnified flexion-extension lateral radiographs, and (2) absence of graft bone bridging (GBB) on CT, defined as the absence of both intragraft bone bridging (inGBB) and extragraft bone bridging (exGBB) (Fig. 2) [9–12]. Both criteria were applied in combination, as concurrent dynamic radiography and CT improve diagnostic accuracy [13]. Fusion was evaluated at each operated level, and in multilevel constructs a patient was classified as having nonunion when nonunion was identified at any one of the operated levels.

# Radiographic variables

Preoperative variables comprised the C2–7 SVA, T1 sagittal slope, global cervical motion (C2–7 Cobb angle excursion on dynamic radiographs), and segmental cervical motion (intervertebral Cobb angle excursion at the operative level).

One-year postoperative variables comprised (1) ISM on 150% magnified flexion-extension radiographs; (2) exGBB and inGBB on CT; and (3) allograft morphological classification proposed by Yang et al.: Type 1 (no change), Type 2 (resorption), Type 3 (fracture), and Type 4 (combined resorption and fracture) (Fig. 3) [14]. We defined Types 2–4 as unfavorable allograft morphology. All continuous parameters were measured independently by two spine surgeons, and one observer repeated all measurements after a 2-week interval; intraobserver and interobserver reliability were assessed using intraclass correlation

coefficients (ICCs). Categorical assessments were determined independently by the same two surgeons, and disagreements were resolved by consensus.

### Clinical variables

Demographic and clinical data comprised age, sex, body mass index (BMI), diagnosis, hypertension (HTN), smoking history, bone mineral density (BMD, T-score), lower-level involvement, and the number of operative levels.

## Statistical analysis

We described continuous variables as mean ± standard deviation and categorical variables as frequency (%). We compared groups using the Mann-Whitney U test for continuous variables and Fisher's exact or chi-square test for categorical variables. Univariable logistic regression was performed for all candidate variables. Before multivariable modeling, variables that were redundant by definition or construct were excluded to avoid multicollinearity: exGBB and inGBB were omitted as constituent components of any GBB, and global cervical motion was excluded because it was highly correlated with segmental motion at the operated level ($r = 0.60$). Variables with $P < 0.05$ on univariable analysis underwent a prespecified stability assessment; a variable was stable when its effect direction was unchanged, its confidence interval overlapped the unadjusted estimate, and significance was retained across all models (Online Resource 1). We fitted the final multivariable model using Firth penalized logistic regression, with confidence intervals and P values based on the profile penalized likelihood. Variables that did not meet the stability criterion are reported as exploratory analyses. We performed receiver operating characteristic (ROC) analysis with Youden index optimization to determine optimal cutoff values for continuous predictors. Statistical significance was set at $P < 0.05$. We performed all analyses in R version 4.5.3 (R Foundation for Statistical Computing, Vienna, Austria).

### Results

## Baseline characteristics

Reliability of the continuous radiographic measurements was moderate, with an interobserver ICC of 0.67 and an intraobserver ICC of 0.72. A total of 119 levels were operated in the 58 patients. Nonunion was observed in 40 of the 119 levels (33.6%). At the patient level, 18 patients (31.0%) achieved fusion between 2 and 5 years (union group) and 40 (69.0%) had persistent nonunion at 5 years (nonunion group), consistent with prior findings [5]. Groups did not differ in age, sex, BMI, BMD, HTN, smoking, number of levels, or lower-level involvement (all $P > 0.05$; Table 1). The diagnostic distribution differed significantly ($P = 0.017$), with myelopathy more common in the union group and myeloradiculopathy more common in the nonunion group.

Table 1
Baseline characteristics of the union and nonunion groups, with between-group comparison

| Variable | Union (n = 18) | Nonunion (n = 40) | P value |
|---|---|---|---|
| **Preoperative variables** | | | |
| Age (years) | 62.39 ± 13.84 | 59.73 ± 9.51 | 0.232 |
| Sex, female | 8 (44.4%) | 16 (40.0%) | 0.976 |
| Sex, male | 10 (55.6%) | 24 (60.0%) | |
| Diagnosis, myelopathy | 12 (66.7%) | 12 (30.0%) | 0.017* |
| Diagnosis, myeloradiculopathy | 1 (5.6%) | 13 (32.5%) | |
| Diagnosis, radiculopathy | 5 (27.8%) | 15 (37.5%) | |
| HTN | 7 (38.9%) | 16 (40.0%) | 1.000 |
| Smoking | 8 (44.4%) | 18 (45.0%) | 1.000 |
| BMD (T-score) | -0.61 ± 1.29 | -0.56 ± 1.17 | 0.812 |
| BMI (kg/m²) | 25.18 ± 3.54 | 24.42 ± 3.09 | 0.573 |
| Lower-level involvement | 17 (94.4%) | 38 (95.0%) | 1.000 |
| Number of levels | 1.78 ± 0.81 | 2.12 ± 0.69 | 0.063 |
| Global cervical ROM (°) | 39.09 ± 11.93 | 47.46 ± 13.14 | 0.024* |
| Segmental motion (°) | 8.31 ± 6.09 | 14.58 ± 8.56 | 0.013* |
| C2–7 SVA (mm) | 20.5 ± 11.49 | 21.97 ± 9.42 | 0.632 |
| T1 sagittal slope (°) | 20.77 ± 7.24 | 23.47 ± 7.75 | 0.220 |
| **1-year postoperative variables** | | | |
| exGBB, present | 4 (22.2%) | 1 (2.5%) | 0.029* |
| inGBB, present | 10 (55.6%) | 5 (12.5%) | 0.001* |
| Any GBB, present | 13 (72.2%) | 6 (15.0%) | < 0.001* |
| Unfavorable allograft morphology (Type 2–4) | 5 (27.8%) | 29 (72.5%) | 0.004* |

Continuous variables are presented as mean ± SD and categorical variables as n (%)

*P < 0.05

ROM range of motion, SVA sagittal vertical axis, HTN hypertension, BMD bone mineral density, BMI body mass index, GBB graft bone bridging, exGBB extragraft bone bridging, inGBB intragraft bone bridging, ISM interspinous motion

| Variable | Union (n = 18) | Nonunion (n = 40) | P value |
|---|---|---|---|
| **Preoperative variables** | | | |
| 1-year ISM (mm) | 2.63 ± 1.42 | 4.57 ± 1.87 | < 0.001* |
| Continuous variables are presented as mean ± SD and categorical variables as n (%) | | | |
| *P < 0.05 | | | |
| ROM range of motion, SVA sagittal vertical axis, HTN hypertension, BMD bone mineral density, BMI body mass index, GBB graft bone bridging, exGBB extragraft bone bridging, inGBB intragraft bone bridging, ISM interspinous motion | | | |

# Preoperative radiographic parameters

Preoperative global cervical motion was significantly greater in the nonunion group (47.46° ± 13.14° vs. 39.09° ± 11.93°; P = 0.024), as was preoperative segmental motion (14.58° ± 8.56° vs. 8.31° ± 6.09°; P = 0.013). In contrast, the C2–7 SVA and T1 sagittal slope did not differ significantly (P = 0.632 and P = 0.220, respectively), consistent with prior findings (Table 1) [6].

# One-year postoperative parameters

All 1-year postoperative variables differed significantly between groups (Table 1). Any GBB was markedly more frequent in the union group (72.2% vs. 15.0%; P < 0.001); inGBB was present in 55.6% versus 12.5% (P = 0.001), and exGBB in 22.2% versus 2.5% (P = 0.029).

Allograft morphology was Type 1 in 24 patients (41.4%), Type 2 in 26 (44.8%), Type 3 in 3 (5.2%), and Type 4 in 5 (8.6%). Unfavorable morphology (Types 2–4) was more prevalent in the nonunion group than in the union group (72.5% vs. 27.8%; P = 0.004). Mean 1-year ISM was also significantly greater in the nonunion group (4.57 ± 1.87 mm vs. 2.63 ± 1.42 mm; P < 0.001) (Table 1).

# Multivariable analysis

Preoperative segmental motion, 1-year ISM, and any GBB met the prespecified stability criteria, whereas unfavorable allograft morphology and myelopathy did not (Online Resource 1); the multivariable model therefore retained three predictors (Table 2). Preoperative segmental motion (OR 1.176; P = 0.006) and 1-year ISM (OR 2.329; P = 0.001) were independently associated with persistent nonunion, whereas any GBB was strongly protective (OR 0.084; P = 0.002). Unfavorable allograft morphology was significant on univariable analysis but was attenuated after adjustment for any GBB (P = 0.053) and is presented as exploratory (Table 3).

Table 2
Univariable and multivariable logistic regression for persistent nonunion at 5 years

| Variable | Univariable OR (95% CI) | P value | Stability | Multivariable OR (95% CI) | P value |
|---|---|---|---|---|---|
| **Preoperative variables** | | | | | |
| Age (years) | 0.979 (0.927–1.029) | 0.412 | | — | — |
| Sex, male | 1.202 (0.394–3.621) | 0.743 | | — | — |
| Diagnosis, myelopathy | 0.228 (0.068–0.704) | 0.010* | Failed | — | — |
| HTN | 1.033 (0.342–3.229) | 0.955 | | — | — |
| Smoking | 1.016 (0.340–3.088) | 0.978 | | — | — |
| BMD (T-score) | 1.033 (0.653–1.642) | 0.888 | | — | — |
| BMI (kg/m²) | 0.933 (0.774–1.104) | 0.426 | | — | — |
| Lower-level involvement | 1.320 (0.115–10.687) | 0.798 | | — | — |
| Number of levels | 2.088 (0.973–4.826) | 0.059 | | — | — |
| Global cervical ROM (°) | 1.050 (1.005–1.102) | 0.027* | a | — | — |
| Segmental motion (°) | 1.131 (1.032–1.287) | 0.005* | Passed | 1.176 (1.041–1.451) | 0.006* |
| C2–7 SVA (mm) | 1.014 (0.960–1.073) | 0.618 | | — | — |

*P < 0.05

[a] Excluded from candidacy a priori to avoid redundancy: exGBB and inGBB are components of any GBB, and global cervical range of motion subsumes segmental motion at the operated level (r = 0.60), which was retained as the mechanistically proximate measure

[b] Did not meet the stability criterion; presented separately in Table 3 as an exploratory analysis

OR odds ratio, CI confidence interval, ROM range of motion, SVA sagittal vertical axis, HTN hypertension, BMD bone mineral density, BMI body mass index, GBB graft bone bridging, exGBB extragraft bone bridging, inGBB intragraft bone bridging, ISM interspinous motion

| Variable | Univariable OR (95% CI) | P value | Stability | Multivariable OR (95% CI) | P value |
|---|---|---|---|---|---|
| **Preoperative variables** | | | | | |
| T1 sagittal slope (°) | 1.047 (0.973–1.138) | 0.227 | | — | — |
| **1-year postoperative variables** | | | | | |
| exGBB, present | 0.122 (0.012–0.733) | 0.021* | a | — | — |
| inGBB, present | 0.125 (0.033–0.430) | 0.001* | a | — | — |
| Any GBB, present | 0.077 (0.019–0.265) | < 0.001* | Passed | 0.084 (0.010–0.425) | 0.002* |
| Unfavorable allograft morphology | 6.296 (1.978–22.559) | 0.002* | Failed | —b | — |
| 1-year ISM (mm) | 2.079 (1.380–3.423) | < 0.001* | Passed | 2.329 (1.391–4.593) | 0.001* |

*P < 0.05

[a] Excluded from candidacy a priori to avoid redundancy: exGBB and inGBB are components of any GBB, and global cervical range of motion subsumes segmental motion at the operated level (r = 0.60), which was retained as the mechanistically proximate measure

[b] Did not meet the stability criterion; presented separately in Table 3 as an exploratory analysis

OR odds ratio, CI confidence interval, ROM range of motion, SVA sagittal vertical axis, HTN hypertension, BMD bone mineral density, BMI body mass index, GBB graft bone bridging, exGBB extragraft bone bridging, inGBB intragraft bone bridging, ISM interspinous motion

Table 3
Exploratory analysis of unfavorable allograft morphology

| Model | OR (95% CI) | P value |
|---|---|---|
| Unadjusted | 6.296 (1.978–22.559) | 0.002 |
| Adjusted for segmental motion | 10.317 (2.637–52.069) | < 0.001 |
| Adjusted for 1-year ISM | 4.740 (1.311–18.910) | 0.018 |
| Adjusted for any GBB | 3.746 (0.985–15.103) | 0.053 |
| Adjusted for diagnosis (myelopathy) | 5.985 (1.786–22.926) | 0.003 |
| Added to the multivariable model | 7.066 (1.145–70.035) | 0.035 |
| The first five rows correspond to the stability assessment for this variable shown in Online Resource 1; the final row reports the estimate obtained when the variable was added to the multivariable model | | |
| OR odds ratio, CI confidence interval, GBB graft bone bridging, ISM interspinous motion | | |

# ROC analysis

ROC analysis identified a preoperative segmental motion cutoff of > 10.05° (sensitivity 67.5%, specificity 66.7%, accuracy 67.2%) and a 1-year ISM cutoff of > 3.62 mm (sensitivity 80.0%, specificity 83.3%, accuracy 81.0%) for predicting persistent nonunion (Table 4, Fig. 4).

Table 4
Receiver operating characteristic analysis of segmental motion and 1-year interspinous motion for persistent nonunion

| Variable | Cutoff | Sensitivity | Specificity | Accuracy |
|---|---|---|---|---|
| Segmental motion (°) | > 10.05° | 67.5% | 66.7% | 67.2% |
| 1-year ISM (mm) | > 3.62 mm | 80.0% | 83.3% | 81.0% |
| Cutoffs were determined by the Youden index; the corresponding curves are shown in Fig. 4 | | | | |
| ISM interspinous motion | | | | |

# Discussion

This study is the third in a longitudinal series examining nonunion after ACDF. The first established that 1-year pseudarthrosis is predominantly a delayed union [4]; the second showed that only 32.6% of patients with 2-year nonunion fused by 5 years, with associated clinical deterioration [5]. In addition to these two studies, the present study identified three independent predictors of persistent nonunion at 5 years in patients with 2-year nonunion after ACDF: preoperative segmental motion more than 10.05°, 1-year ISM more than 3.62 mm, and absence of GBB (Fig. 5). Unfavorable allograft morphology showed a strong but exploratory association.

The finding that preoperative segmental motion predicts pseudarthrosis is consistent with Choi et al., who reported a 12° cutoff with an AUC of 0.899 [6]. In our cohort, the optimal threshold was slightly lower, at 10.05°. This difference likely reflects our more specific analytic target: we analyzed only patients in whom nonunion was observed at 2 years. Excessive preoperative segmental motion reflects intrinsic instability that produces persistent micromotion at the graft-endplate interface, which inhibits bone formation at the fusion site [6]. Even when solid fusion is ultimately achieved, the greater intrinsic elasticity of the bone and facet joints in these segments can generate residual micromotion through elastic deformation [15, 16].

One-year ISM greater than 3.62 mm was a significant predictor. Persistent motion at the instrumented segment at 1 year indicates that the plate-screw construct and callus have not yet established adequate stabilization for bone bridging. A prior study proposed a 4-mm cutoff at 6 months postoperatively as a risk factor for nonunion at 24 months [7]. However, the 6-month assessment is limited, as inadequate patient cooperation or neck pain may restrict maximal flexion–extension and bone healing after ACDF continues through the first and second postoperative years [5, 17, 18]. The 1-year time point and the 3.62-mm cutoff identified in this study are therefore more clinically appropriate thresholds for predicting whether nonunion observed at 2 years will persist to 5 years.

Unfavorable allograft morphology showed the largest effect magnitude on univariable analysis (OR 6.296; P = 0.002), although this association did not meet our stability criterion and is therefore reported as exploratory. Structural allograft failure indicates irreversible loss of the mechanical scaffold required for fusion. Two interrelated mechanisms, described by Yang et al. [14], account for this association. First, a reduction in graft height loosens the construct and increases segmental micromotion during extension and axial rotation [19, 20]. Second, the loss of graft height progressively diminishes the segmental lordosis achieved at surgery, although overall cervical lordosis is maintained through compensation at the unoperated segments [21]. However, because both were assessed at 1 year, their temporal relationship could not be established: it is unclear whether failure of union precipitates graft resorption or fracture, or whether morphological deterioration of the graft itself prevents union, and adjustment for bridging may have attenuated an effect that is in part mediated through it.

The protective effect of GBB (OR 0.084) confirms early bone bridging as the most favorable prognostic indicator in this cohort. GBB was present at 1 year in 72.2% of patients with union, whereas it was absent in 85.0% of those with persistent nonunion. This finding is consistent with prior validation studies confirming that extragraft and intragraft bone bridging on CT are reliable indicators of fusion after ACDF [8, 13, 22].

# Clinical implications

Patients with preoperative segmental motion > 10.05°, 1-year ISM > 3.62 mm, and absent GBB together with worsening clinical symptoms are candidates for early intervention, including additional surgery, rather than continued observation. Pharmacologic adjuncts are also an option: teriparatide accelerates

spinal fusion in osteoporotic bone [23], and in 20 patients with delayed union or nonunion of extremity fractures, teriparatide treatment was associated with union in 80% of patients at 3 months and 85% at 6 months; although derived from extremity fractures rather than a spinal cohort, adjunctive teriparatide may be considered in selected patients with persistent nonunion [24].

# Limitations

This study has several limitations. First, the small sample size (n = 58) reflects the rarity of patients who remain ununited at 2 years after ACDF and limits the statistical precision of the model. With only 18 union events, the final model retained three predictors, giving an events-per-variable ratio of 6.0 for the final model, below the conventional threshold of 10. The candidate set and the stability criterion were prespecified, and Firth penalized logistic regression was used to reduce small-sample bias and separation. Second, the retrospective, single-institution design limits generalizability, and because a corticocancellous allograft served as the interbody spacer in all patients, the findings do not extend to other spacer materials such as polyetheretherketone or titanium cages [21, 25]. Third, clinical outcomes such as VAS and NDI were not included as candidate predictors, because the association between persistent nonunion and worsening of these outcomes has already been established [5]. Fourth, the study did not include nutritional assessments of patients both pre- and post-surgery. Therefore, the impact of diet, supplements, and other medications on the results cannot be considered. Fifth, unfavorable allograft morphology was significantly associated with persistent nonunion on univariable analysis but did not meet the stability criterion and is reported only as an exploratory finding.

## Conclusions

Preoperative segmental motion > 10.05°, 1-year ISM > 3.62 mm, and the absence of GBB are independent predictors of persistent nonunion at 5 years following ACDF; unfavorable allograft morphology shows a consistent but exploratory association. Patients who display these adverse radiographic parameters together with worsening clinical symptoms are candidates for early revision surgery rather than continued expectant observation.

## Declarations

# Author Contribution

Conceptualization: D.H.L., C.H.D.Methodology: C.H.D., S.T.C., S.PResources: D.H.L., C.J.H., J.H.C., S.P.Investigation: S.T.C., C.H.D., S.P.Data curation: S.T.C., C.H.D.Formal analysis: C.H.D., S.T.C., S.P.Writing – original draft: C.H.D.; Writing – review and editing: all authorsSupervision: D.H.L.Project administration: D.H.L. All authors read and approved the final manuscript and agree to be accountable for all aspects of the work.

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# Figures

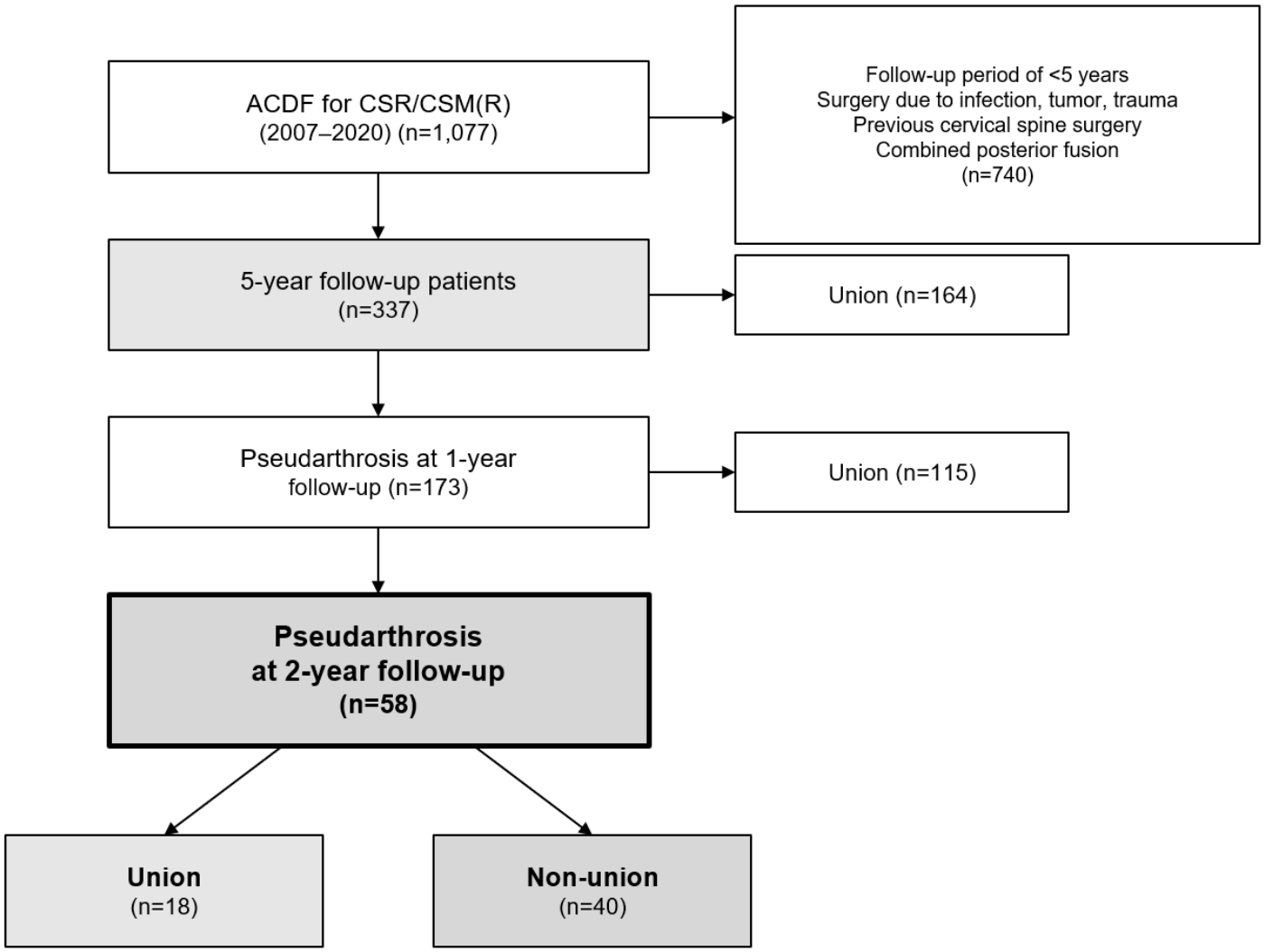


**Figure 1**

Flow diagram of patient selection. Of 1,077 patients who underwent anterior cervical discectomy and fusion for cervical radiculopathy or myelopathy between 2007 and 2020, 337 completed a minimum 5-year follow-up, 173 showed pseudarthrosis at 1 year, and 58 had persistent nonunion at 2 years, of whom 18 achieved union and 40 remained ununited at 5 years

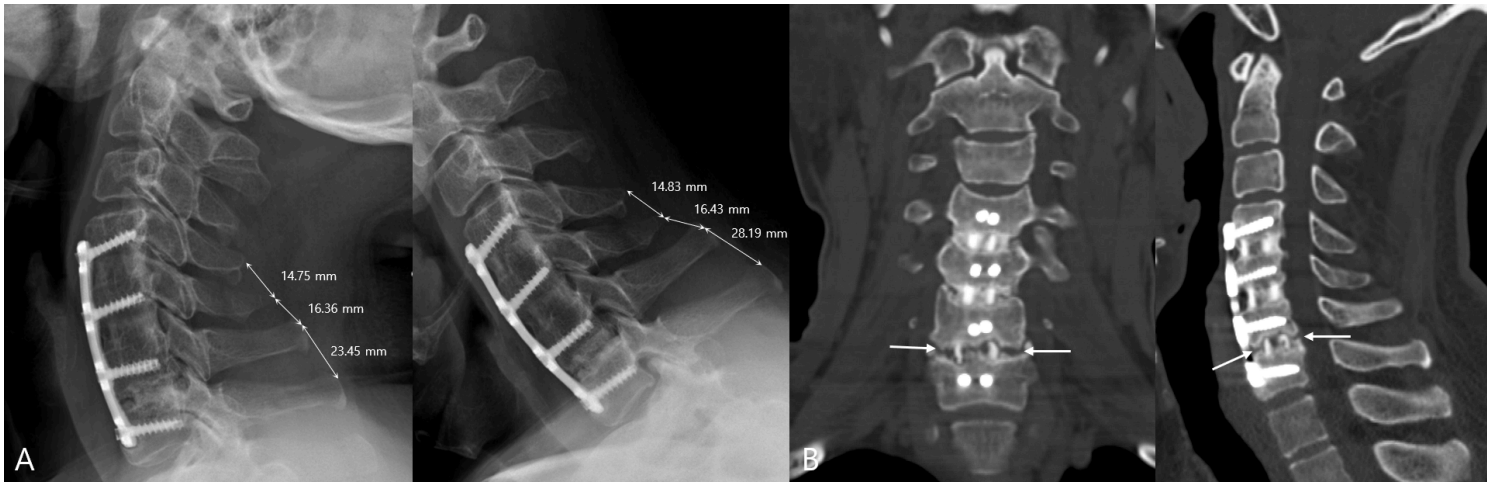


**Figure 2**

Radiographic assessment of nonunion. A Magnified flexion-extension lateral radiographs with interspinous distances measured at each operated level. B Coronal and sagittal computed tomography reconstructions; arrows indicate absence of intragraft and extragraft bone bridging

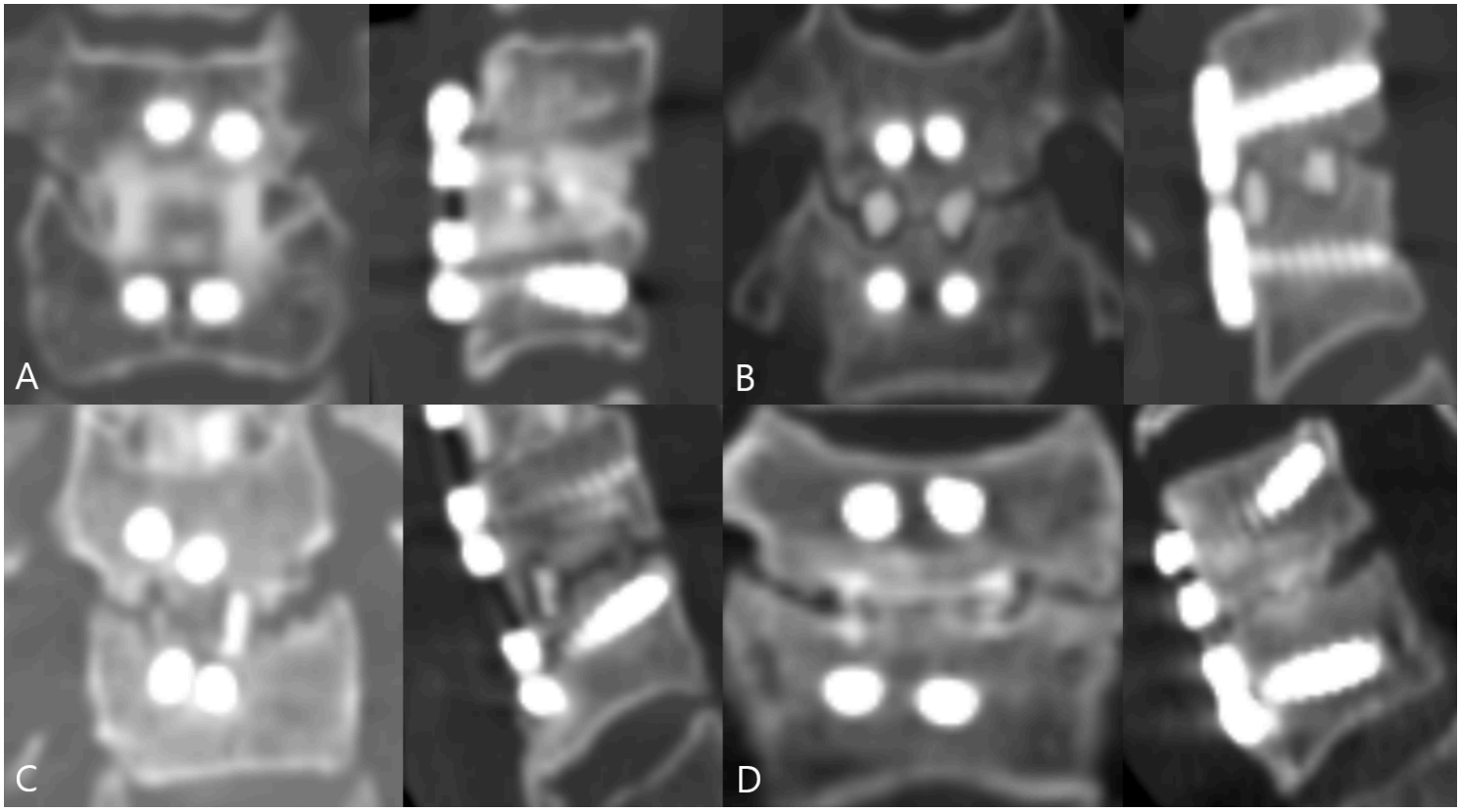


**Figure 3**

Allograft morphology on computed tomography at 1 year. A Type 1, no change. B Type 2, resorption. C Type 3, fracture. D Type 4, combined resorption and fracture

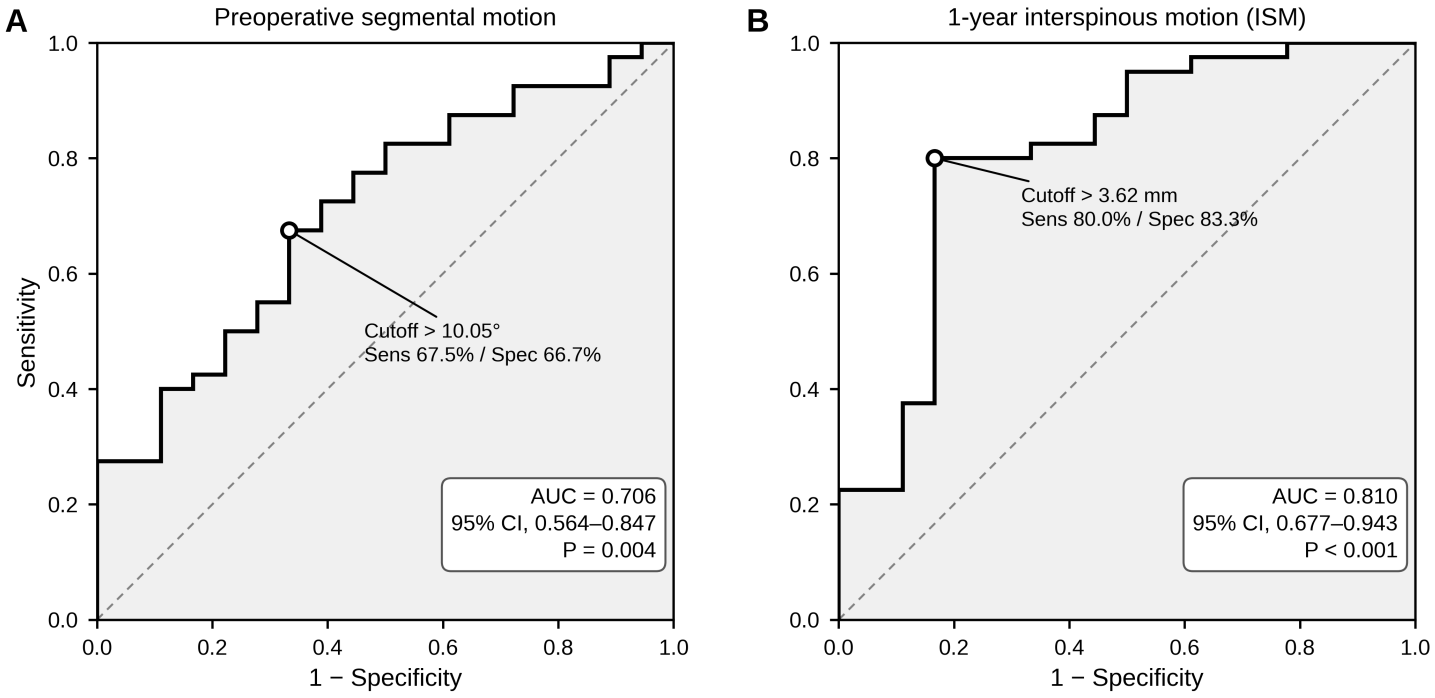


**Figure 4**

Receiver operating characteristic curves for predicting persistent nonunion at 5 years. A Preoperative segmental motion. B One-year interspinous motion. Circles denote the optimal cutoff determined by the Youden index

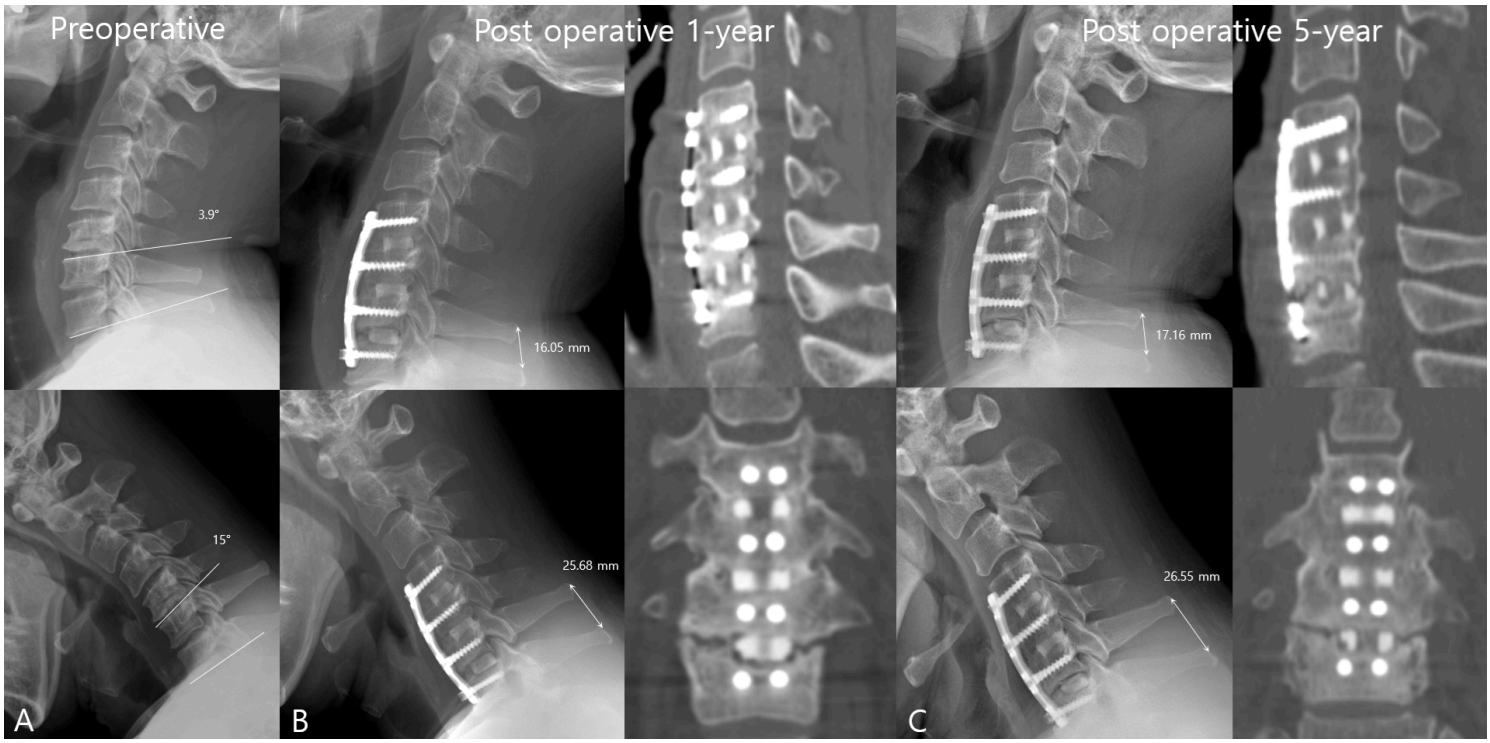


**Figure 5**

Representative cases. A Preoperative flexion-extension radiographs with segmental motion. B One-year radiographs and computed tomography showing interspinous motion and graft bone bridging status. C Five-year radiographs and computed tomography showing final fusion status.

## Supplementary Files

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- Onlineresource1.pdf