



# EARLY MOTION PRESERVATION BUT CONVERGING TWO-YEAR OUTCOMES AFTER CERVICAL DISC ARTHROPLASTY VERSUS ANTERIOR CERVICAL DISCECTOMY AND FUSION: A RETROSPECTIVE COHORT STUDY

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## ABSTRACT

**Objective:** This study compared cervical alignment, pain, cervical range of motion (ROM), and implant-related radiological findings between single-level anterior cervical discectomy and fusion (ACDF) and cervical disc arthroplasty (CDA).

**Materials and Methods:** This retrospective comparative cohort study included 96 patients who underwent single-level anterior cervical surgery between 2015 and 2024, of whom 50 underwent ACDF and 46 underwent CDA. Sagittal and coronal cervical Cobb angles, visual analog scale (VAS) pain scores, total cervical ROM, and directional movements were assessed preoperatively and at 6 months, 1 year, and 2 years postoperatively. Implant-related bone changes and heterotopic ossification were evaluated. Between-group comparisons were analyzed using independent-samples t-tests and Fisher's exact tests, whereas longitudinal changes were analyzed using linear mixed-effects models.

**Results:** Sagittal and coronal Cobb angles did not differ significantly between the groups at any time point. VAS pain scores improved significantly over time in both groups, without a significant between-group difference. Total cervical ROM decreased to a lesser extent after CDA than after ACDF at 6 months and 1 year (both  $p < 0.001$ ), but not at 2 years ( $p = 0.623$ ). Similar early- and mid-term advantages were observed for flexion, extension, and bilateral lateral flexion. Significant group-by-time interactions were identified for total ROM and directional movements. Most implant-related radiological findings were comparable between the groups; however, segmental collapse was significantly more frequent after ACDF than after CDA (20.0% vs. 2.2%;  $p = 0.008$ ). In the CDA group, grade III heterotopic ossification occurred in 8.7% of patients, and grade IV functional fusion occurred in 4.3% of patients.

**Conclusion:** ACDF and CDA provided comparable pain relief and cervical alignment outcomes. CDA better preserved cervical mobility during early and midterm follow-up; however, this advantage was not maintained at 2 years. Segmental collapse was less frequent after CDA, although larger studies are required to confirm differences in implant-related complications.

**Keywords:** ACDF, CDA, cervical spine, range of motion, Cobb angle, heterotopic ossification

## INTRODUCTION

Cervical disc herniation and degenerative cervical disc disease are common spinal pathologies that may cause pain, neurological deficits, and functional limitations through radiculopathy or myelopathy. In patients who do not respond to conservative treatment or who develop progressive neurological findings, surgical treatment represents one of the principal therapeutic options. Although neural decompression remains the primary objective of surgery, preservation or

restoration of cervical sagittal alignment and cervical mobility has become increasingly important in evaluating postoperative outcomes<sup>(1,2)</sup>.

Anterior cervical discectomy and fusion (ACDF) is a widely used and reliable surgical technique for the treatment of single-level cervical degenerative disc disease. In ACDF, neural decompression and segmental stability are achieved through discectomy and interbody fusion. However, elimination of motion at the operated segment may increase mechanical loading and compensatory movement at adjacent cervical levels over time<sup>(2,3)</sup>.

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Cervical disc arthroplasty (CDA), in contrast, was developed as a motion-preserving alternative to fusion. Its theoretical advantages include preservation of index-level mobility, maintenance of more physiological cervical biomechanics, reduction of adjacent-segment loading, and improved preservation of cervical sagittal alignment<sup>(4)</sup>.

Radiological parameters such as the C2-C7 Cobb angle, segmental lordosis, cervical sagittal vertical axis, and posterior tangent-based measurements are used to evaluate cervical sagittal alignment<sup>(4)</sup>. Although the C2-C7 Cobb angle is one of the most commonly used measures of cervical lordosis, degenerative endplate changes and osteophytes may affect its reliability<sup>(5)</sup>. Evaluation of cervical alignment using more than one radiological parameter may therefore provide a more comprehensive assessment of postoperative changes.

Previous studies have demonstrated that both ACDF and CDA produce favorable clinical outcomes. CDA may provide additional advantages in terms of motion preservation and adjacent-segment biomechanics, particularly during early and mid-term follow-up. Nevertheless, these advantages may diminish over time because of heterotopic ossification, progressive restriction of prosthetic motion, periprosthetic bone changes, or functional fusion of the operated segment<sup>(6,7)</sup>.

Evidence regarding the simultaneous longitudinal evaluation of cervical alignment, pain, cervical range of motion (ROM), and implant-related bone changes remains limited. A comparative evaluation of the magnitude and temporal pattern of differences between ACDF and CDA may therefore provide clinically relevant information regarding postoperative recovery.

Therefore, the aim of this study was to compare early, mid-term, and late radiological and clinical outcomes after single-level ACDF and CDA, with particular emphasis on cervical Cobb angles, pain intensity, cervical ROM, and implant-related radiological changes.

The primary hypothesis was that CDA would provide better preservation of cervical ROM than ACDF during early and mid-term follow-up. The secondary hypothesis was that the difference between the procedures would decrease during late follow-up.

## MATERIALS AND METHODS

### Study Design and Patient Population

This study was designed as a retrospective comparative cohort study. Patients who underwent single-level anterior cervical surgery for cervical disc herniation or degenerative cervical disc disease between 2015 and 2024 were screened retrospectively. As this study involved the retrospective use of patient data, the necessary institutional permission was obtained in accordance with the applicable regulations on the protection of personal data. Ethical approval was obtained from the Nuh Naci Yazgan University Non-Interventional Clinical Research Ethics Committee (approval no: 2026/04-001, date: 16.04.2026).

Institutional permission was granted by the Kayseri Provincial Directorate of Health, Public Hospitals Services Presidency (approval no: E-29701769-619-299456034, date: 29.12.2025) and officially communicated under letter no: E-94068515-619-299696227, date: 30.12.2025. All patient data were anonymized before analysis, and the study was conducted in accordance with the principles of the Declaration of Helsinki.

A total of 96 patients were included in the analysis. Fifty patients who underwent ACDF with cage implantation constituted the ACDF group, while 46 patients who underwent CDA with disc prosthesis implantation constituted the CDA group.

The sample was selected from patients with complete preoperative and postoperative radiological and clinical follow-up data. To improve comparability between the surgical groups, patients were selected according to predefined eligibility criteria. Where applicable, the groups were balanced with regard to age, sex, operated cervical level, primary diagnosis, and clinical presentation.

Treatment allocation was non-random and reflected routine clinical practice. The choice between ACDF and CDA was made by the treating surgeon based on the overall clinical and radiological assessment. In general, CDA was considered in patients with preserved index-level mobility, acceptable sagittal alignment, and without advanced facet degeneration or segmental instability, whereas ACDF was preferred when motion-preserving surgery was considered less appropriate. Because of the retrospective design, the relative contribution of individual factors to treatment selection could not be quantified.

Patients were included if they had clinically and radiologically confirmed single-level cervical disc herniation or degenerative cervical disc disease that was unresponsive to conservative treatment and had sufficient preoperative and postoperative radiological and clinical follow-up data. Patients who had undergone multilevel surgery, had a history of trauma, underwent surgery for tumor-related pathology, had revision surgery, had a history of malignancy, active regional infection, advanced osteoporosis, or insufficient radiological or clinical documentation were excluded from the study. Advanced osteoporosis was defined as the presence of advanced osteoporosis in clinical records or a bone mineral density T-score of  $\leq -2.5$ .

### Surgical Technique

All patients underwent surgery using a standard anterior cervical approach. After confirmation of the surgical level under fluoroscopic guidance, discectomy was performed and neural decompression was achieved. When necessary, posterior osteophytes and disc fragments causing nerve root or spinal cord compression were removed.

In the ACDF group, after discectomy, the intervertebral space was prepared and a cage was inserted to provide segmental stability and fusion. The cage type and the need for additional stabilization were determined according to the surgeon's

preference, the patient's anatomical characteristics, and intraoperative findings. The main objective of ACDF is to achieve neural decompression, restore disc height, provide segmental stability, and obtain fusion<sup>(2,3)</sup>.

In the CDA group, after discectomy and decompression, an appropriately sized mobile cervical disc prosthesis was implanted while preserving the endplates as much as possible. The main objective of CDA is to preserve index-level motion, restore disc height, and maintain more physiological cervical spine biomechanics while achieving neural decompression<sup>(4)</sup>.

### Outcome Measures

The primary outcome measure was the change in total cervical ROM from the preoperative assessment to the postoperative follow-up periods. Total cervical ROM was calculated as the sum of cervical flexion, extension, right and left lateral flexion, and right and left rotation measured at each assessment.

Secondary clinical outcomes included changes in visual analog scale (VAS) pain score and the individual cervical movement directions used to derive total ROM, including flexion, extension, bilateral lateral flexion, and bilateral rotation. Accordingly, total ROM and directional ROM outcomes were not statistically independent; directional analyses were performed to characterize the movement-specific components underlying the overall ROM findings. Secondary radiological outcomes included sagittal and coronal cervical Cobb angles, osteolysis, periprosthetic or anterior bone loss, radiological findings suggestive of osteonecrosis, implant subsidence, implant migration, segmental collapse, revision surgery, and heterotopic ossification in the CDA group.

### Radiological Assessment

Radiological assessments were performed using standard anteroposterior and lateral cervical radiographs obtained preoperatively and at the postoperative 6 month, 1 year, and 2 year follow-ups. Sagittal cervical alignment was evaluated on lateral radiographs using the C2-C7 Cobb angle, whereas coronal cervical alignment was evaluated on anteroposterior radiographs.

#### C2-C7 Cobb Angle

The C2-C7 Cobb angle was measured on lateral cervical radiographs as the angle between the inferior endplate of the C2 vertebra and the inferior endplate of the C7 vertebra. The Cobb angle is a widely used and clinically accepted parameter for evaluating cervical lordosis<sup>(1,5)</sup>.

### Assessment of Osteolysis, Periprosthetic Bone Loss, and Osteonecrosis

Implant-related bone changes were also evaluated on postoperative follow-up radiographs. In patients who underwent CDA, radiolucent areas around the prosthesis, cystic bone loss adjacent to the endplate, anterior vertebral body resorption, progressive periprosthetic bone loss, implant subsidence, and implant migration were assessed in terms of osteolysis/

periprosthetic bone loss. In the ACDF group, radiolucent lines around the cage, endplate subsidence, segmental collapse, cage migration, and osteolysis-like bone loss findings were evaluated.

The literature reports that bone loss observed after CDA does not always indicate true inflammatory osteolysis and may be associated with different mechanisms, including stress-related bone remodeling, periprosthetic infection, wear particle-induced inflammatory osteolysis, avascular necrosis, and hydrostatic pressure<sup>(8,9)</sup>. Therefore, in the present study, limited, early, and non-progressive anterior bone resorption was recorded as "periprosthetic/anterior bone loss", whereas progressive radiolucent or cystic bone loss around the implant was recorded as "osteolysis".

When image quality was sufficient, the severity of bone loss was classified according to the proportion of subchondral bone loss. Accordingly, bone loss was classified as mild if it involved 1-5%, moderate if it involved 6-10%, and severe if it involved >10%; the presence of vertebral collapse was also recorded separately<sup>(8)</sup>. In patients with suspected endplate-level osteolysis around the cervical disc prosthesis, the principles of the total disc replacement osteolysis grading scale were considered when the available imaging data were sufficient. According to this classification, grade 0 indicates no osteolysis, grade 1 indicates osteolysis involving <50% of one endplate, grade 2 indicates osteolysis involving <50% of both endplates, grade 3 indicates osteolysis involving ≥50% of one endplate, and grade 4 indicates osteolysis involving ≥50% of both endplates<sup>(10)</sup>.

Radiological findings suggestive of osteonecrosis/avascular necrosis were assessed based on the presence of vertebral body sclerosis, intravertebral radiolucent or vacuum-like areas, progressive loss of vertebral height, or collapse. In patients with suspected osteonecrosis, available CT or MRI records were used when present. On MRI, avascular/non-enhancing areas, intravertebral fluid, or air findings are considered descriptive features of osteonecrosis<sup>(11,12)</sup>. However, because the mechanism of osteonecrosis cannot be definitively confirmed using plain radiographs alone, these findings were recorded in the present study as "radiological findings suggestive of osteonecrosis".

All radiological measurements were performed by the same evaluator to reduce measurement variability. Radiographs with insufficient image quality or in which anatomical reference points could not be reliably identified were excluded from the relevant analysis.

### Clinical Assessment

Clinical outcomes were evaluated based on pain intensity and cervical ROM. Clinical assessments were performed preoperatively and at the postoperative 6<sup>th</sup> month, 1<sup>st</sup> year, and 2<sup>nd</sup> year follow-ups. The postoperative 6<sup>th</sup> month was considered the early follow-up period, the 1<sup>st</sup> year was considered the mid-term follow-up period, and the 2<sup>nd</sup> year was considered the late follow-up period<sup>(6,7)</sup>.

### Pain Score

Pain intensity was evaluated using the VAS, a widely used unidimensional measure of self-reported pain intensity<sup>(13,14)</sup>. Patients were asked to rate their pain on a scale from 0 to 10, where 0 indicated no pain and 10 indicated the worst or unbearable pain. VAS scores recorded preoperatively and at the postoperative 6 month, 1 year, and 2 year follow-ups were used to evaluate longitudinal changes in pain intensity in both surgical groups.

The ACDF/cage and CDA/prosthesis groups were compared in terms of preoperative and postoperative VAS scores. The general pain score documented in the clinical records was used for analysis.

### Cervical ROM Assessment

Cervical ROM was evaluated as a functional indicator of global cervical mobility. Cervical flexion, extension, right and left lateral flexion, and right and left rotation measurements recorded in the clinical follow-up files were analyzed. All measurements were expressed in degrees.

For each assessment time point, total cervical ROM was calculated as the arithmetic sum of the six directional movement measurements: flexion, extension, right lateral flexion, left lateral flexion, right rotation, and left rotation. Therefore, total cervical ROM represented a derived composite measure rather than an independently measured variable. The individual directional ROM measurements were additionally analyzed to determine which movement components contributed to the observed changes in total cervical mobility.

Because CDA is a motion-preserving surgical technique, cervical ROM was expected to be better preserved after CDA, particularly during early and mid-term follow-up. However, it was also considered that this difference could decrease in the late period because of heterotopic ossification, segmental motion loss, periprosthetic bone changes, or the prosthesis functionally behaving in a fusion-like manner<sup>(4,6,7)</sup>.

### Assessment of Heterotopic Ossification

Heterotopic ossification was evaluated only in the CDA group using postoperative radiographs. Findings were classified from grade 0 to grade 4 according to the adopted radiographic grading system. Grade 0 indicated no heterotopic ossification, grades 1 and 2 indicated bone formation without clinically relevant restriction of prosthetic motion, grade 3 indicated motion-restricting heterotopic ossification, and grade 4 indicated complete functional fusion of the operated segment.

### Statistical Analysis

Continuous variables were presented as mean  $\pm$  standard deviation, and categorical variables were presented as number and percentage. The normality of continuous variables was evaluated using the Shapiro-Wilk test and visual inspection of distribution plots. Baseline continuous variables were compared

between the ACDF and CDA groups using the independent-samples t-test. Categorical variables were compared using the chi-square test or Fisher's exact test, as appropriate.

Between-group comparisons of sagittal and coronal Cobb angle measurements at each assessment were performed using the independent-samples t-test. Change scores were calculated by subtracting the preoperative value from the corresponding follow-up value. Between-group comparisons of change scores were also performed using the independent-samples t-test.

Longitudinal changes were analyzed using linear mixed-effects models. Time, surgical group, and the group $\times$ time interaction were included as fixed effects, and patient was included as a random effect. The group $\times$ time interaction was used to determine whether the pattern of longitudinal change differed between the ACDF and CDA groups. A two-sided p-value of  $<0.05$  was considered statistically significant.

## RESULTS

A total of 96 patients were included in the study. The mean age was  $43.8 \pm 9.6$  years in the ACDF/cage group and  $44.5 \pm 8.9$  years in the CDA/prosthesis group ( $p=0.674$ ). The groups were similar in terms of sex distribution, body mass index (BMI), clinical presentation, operated cervical level, and follow-up duration (all  $p>0.05$ ) (Table 1).

The longitudinal cervical Cobb angle measurements are presented in Table 2. No statistically significant differences were observed between the groups in sagittal Cobb angle at the preoperative, 6 month, 1 year, or 2 year assessments (all  $p>0.05$ ). Similarly, coronal Cobb angles did not differ significantly between the groups at any assessment time point (all  $p>0.05$ ) (Table 2).

Changes in cervical Cobb angles from baseline are shown in Table 3. At 6 months, 1 year, and 2 years, the changes in sagittal Cobb angle did not differ significantly between the ACDF/cage and CDA/prosthesis groups ( $p=0.140$ ,  $p=0.288$ , and  $p=0.440$ , respectively). No statistically significant between-group differences were found in coronal Cobb angle changes at 6 months, 1 year, or 2 years ( $p=0.383$ ,  $p=0.282$ , and  $p=0.112$ , respectively) (Table 3).

Absolute VAS pain scores and cervical ROM measurements, together with changes from baseline, are presented in Table 4. At the preoperative assessment, there were no statistically significant differences between the ACDF/cage and CDA/prosthesis groups in VAS pain score, total cervical ROM, or any directional ROM measurement (all  $p>0.05$ ), indicating comparable baseline pain intensity and global cervical mobility between the groups.

VAS pain scores decreased substantially in both groups during follow-up. Absolute VAS scores did not differ significantly between the groups at 6 months, 1 year, or 2 years (all  $p>0.05$ ). Similarly, changes in VAS scores from baseline were comparable between the groups at 6 months, 1 year, and 2 years (all  $p>0.05$ ) (Table 4).

At 6 months, absolute total cervical ROM was significantly greater in the CDA/prosthesis group than in the ACDF/cage group ( $276.2 \pm 29.6^\circ$  vs.  $251.2 \pm 30.1^\circ$ ;  $p < 0.001$ ). This difference remained significant at 1 year ( $280.9 \pm 28.9^\circ$  vs.  $262.8 \pm 29.7^\circ$ ;  $p = 0.003$ ), whereas no significant between-group difference was observed at 2 years ( $271.7 \pm 30.5^\circ$  vs.  $269.4 \pm 30.2^\circ$ ;  $p = 0.711$ ). Consistent with these absolute values, the reduction in total cervical ROM from baseline was significantly greater in the ACDF/cage group than in the CDA/prosthesis group at 6 months ( $-43.8 \pm 24.6^\circ$  vs.  $-18.8 \pm 26.1^\circ$ ;  $p < 0.001$ ) and 1 year ( $-32.2 \pm 23.9^\circ$  vs.  $-14.1 \pm 25.4^\circ$ ;  $p < 0.001$ ). At 2 years, the change in total cervical ROM did not differ significantly between the groups ( $p = 0.623$ ) (Table 4).

For directional ROM, absolute flexion, extension, and bilateral lateral flexion values were significantly greater in the CDA/prosthesis group at 6 months and 1 year (all  $p < 0.05$ ), whereas no significant differences were observed at 2 years. Absolute right and left rotation values did not differ significantly between the groups at any postoperative assessment (all  $p > 0.05$ ). Analysis of change scores showed greater reductions in the ACDF/cage group for flexion, extension, bilateral lateral flexion, and bilateral rotation at 6 months (all  $p < 0.05$ ). At 1 year, significant between-group differences in change from baseline remained for flexion, extension, and bilateral lateral flexion, whereas the differences in right and left rotation were no longer statistically significant. At 2 years, no significant between-group differences were observed in the change from baseline for any individual cervical movement direction (all  $p > 0.05$ ) (Table 4).

Implant-related radiological findings are presented in Table 5. At least one implant-related bone change was observed in 10 patients (20.0%) in the ACDF/cage group and 13 patients (28.2%) in the CDA/prosthesis group, with no statistically significant between-group difference. Osteolysis and periprosthetic or anterior bone loss were numerically more frequent in the CDA group, although the differences did not reach statistical significance. Radiological findings suggestive of osteonecrosis, implant subsidence, implant migration, and revision surgery rates were also comparable between the groups. Segmental collapse was significantly more frequent in the ACDF/cage group than in the CDA/prosthesis group (20.0% vs. 2.2%;  $p = 0.008$ ). In the CDA/prosthesis group, heterotopic ossification was classified as grade 0 in 24 patients (52.2%), grade 1 in 8 patients (17.4%), grade 2 in 8 patients (17.4%), grade 3 in 4 patients (8.7%), and grade 4, indicating functional fusion, in 2 patients (4.3%).

The longitudinal model results are presented in Table 6. Significant time effects were observed for sagittal Cobb angle, coronal Cobb angle, VAS pain score, total cervical ROM, and all individual ROM measurements (all  $p < 0.05$ ). Significant group effects were found for total cervical ROM, flexion ROM, extension ROM, and left lateral flexion ROM (all  $p < 0.05$ ) (Table 6).

Significant group-by-time interactions were observed for total cervical ROM ( $p = 0.004$ ), flexion ROM ( $p = 0.012$ ), extension ROM ( $p = 0.006$ ), right lateral flexion ROM ( $p = 0.018$ ), and left lateral flexion ROM ( $p = 0.021$ ). The group-by-time interactions were

**Table 1.** Baseline demographic and surgical characteristics of the patients

| Variable                           | ACDF/cage group (n=50)<br>mean $\pm$ SD | CDA/prosthesis group (n=46)<br>mean $\pm$ SD | p-value |
|------------------------------------|-----------------------------------------|----------------------------------------------|---------|
| Age, years                         | 43.8 $\pm$ 9.6                          | 44.5 $\pm$ 8.9                               | 0.674   |
| Sex, n (%)                         |                                         |                                              |         |
| Female                             | 30 (60.0)                               | 25 (54.3)                                    | 0.582   |
| Male                               | 20 (40.0)                               | 21 (45.7)                                    |         |
| BMI, kg/m <sup>2</sup>             | 27.1 $\pm$ 3.8                          | 26.7 $\pm$ 4.1                               | 0.593   |
| Diagnosis, n (%)                   |                                         |                                              |         |
| Cervical disc herniation           | 35 (70.0)                               | 35 (76.0)                                    | 0.646   |
| Degenerative cervical disc disease | 15 (30.0)                               | 11 (24.0)                                    |         |
| Clinical presentation, n (%)       |                                         |                                              |         |
| Radiculopathy                      | 42 (84.0)                               | 37 (80.4)                                    | 0.790   |
| Myelopathy                         | 8 (16.0)                                | 9 (19.6)                                     |         |
| Operated level, n (%)              |                                         |                                              |         |
| C3-4                               | 5 (10.0)                                | 5 (10.9)                                     | 0.945   |
| C4-5                               | 7 (14.0)                                | 8 (17.4)                                     |         |
| C5-6                               | 25 (50.0)                               | 23 (50.0)                                    |         |
| C6-7                               | 13 (26.0)                               | 10 (21.7)                                    |         |
| Follow-up duration, months         | 26.4 $\pm$ 5.8                          | 25.9 $\pm$ 6.2                               | 0.647   |

Continuous variables were compared between the anterior cervical discectomy and fusion (ACDF) and cervical disc arthroplasty (CDA) groups using the independent-samples t-test. \*: Categorical variables were compared using the chi-square test or Fisher's exact test, as appropriate. Data are presented as mean  $\pm$  standard deviation (SD) or n (%), as appropriate, BMI: Body mass index

not statistically significant for sagittal Cobb angle, coronal Cobb angle, VAS pain score, right rotation ROM, or left rotation ROM (Table 6).

## DISCUSSION

This retrospective study compared the early, mid-term, and late radiological and clinical outcomes of single-level ACDF and CDA. The principal findings were that sagittal and coronal cervical Cobb angle changes and pain reduction were similar between the two procedures, whereas CDA was associated with better preservation of total cervical ROM during the early and mid-term follow-up periods. However, the between-group differences in total and directional cervical ROM were no longer significant at the 2 year follow-up. Periprosthetic or anterior bone loss was numerically more frequent in the CDA group but did not differ significantly between the procedures. Most implant-related radiological findings were also comparable; however, segmental collapse was significantly more frequent in the ACDF group.

The ACDF and CDA groups were comparable in terms of age, sex, BMI, clinical presentation, operated level, and follow-up duration. This baseline similarity reduced the likelihood that the observed postoperative differences were primarily attributable to major demographic or surgical-level imbalances. Nevertheless, treatment selection in retrospective studies

may still be influenced by factors such as facet degeneration, baseline segmental mobility, endplate condition, sagittal alignment, bone quality, and surgeon preference. These factors are particularly relevant because CDA is generally selected for patients with preserved segmental mobility and without advanced facet arthropathy or severe instability<sup>(15,16)</sup>.

Sagittal Cobb angles did not differ significantly between the groups at baseline or during any postoperative follow-up assessment. Moreover, the changes from baseline showed no significant between-group differences. These findings indicate that neither surgical method demonstrated a clear advantage in preserving global cervical sagittal alignment during the 2 year follow-up period. Although CDA is intended to maintain physiological segmental biomechanics, its effect on global C2-C7 alignment may depend on preoperative alignment, prosthesis design and positioning, index-level angle, operated level, and compensatory changes occurring at the adjacent segments. Previous evidence comparing single-level ACDF and CDA has similarly shown that postoperative differences in global cervical lordosis are often small or inconsistent, despite differences in index-level motion<sup>(17)</sup>.

A significant overall time effect was observed for sagittal Cobb angle, but neither the group effect nor the group-by-time interaction was significant. Therefore, the longitudinal change in sagittal alignment appeared to occur similarly in both groups rather than being specific to either ACDF or CDA.

**Table 2.** Longitudinal changes in cervical Cobb angles

| Parameter                | Time point   | ACDF/cage group (n=50)<br>mean ± SD | CDA/prosthesis group (n=46)<br>mean ± SD | p-value |
|--------------------------|--------------|-------------------------------------|------------------------------------------|---------|
| Sagittal Cobb angle, (°) | Preoperative | 17.60±6.28                          | 16.71±5.93                               | 0.432   |
|                          | 6 month      | 16.98±4.81                          | 17.78±6.42                               | 0.431   |
|                          | 1 year       | 16.01±4.47                          | 16.43±5.00                               | 0.633   |
|                          | 2 years      | 15.43±3.61                          | 15.66±3.78                               | 0.755   |
| Coronal Cobb angle, (°)  | Preoperative | 1.64±0.61                           | 1.61±0.59                                | 0.766   |
|                          | 6 month      | 1.65±0.55                           | 1.74±0.85                                | 0.503   |
|                          | 1 year       | 1.41±0.46                           | 1.50±0.64                                | 0.364   |
|                          | 2 years      | 1.27±0.42                           | 1.35±0.55                                | 0.417   |

Independent-samples t-test. Data are presented as mean ± standard deviation (SD). ACDF: Anterior cervical discectomy and fusion, CDA: Cervical disc arthroplasty

**Table 3.** Changes in cervical Cobb angles from baseline

| Parameter                | Follow-up | ACDF/cage group (n=50)<br>mean ± SD | CDA/prosthesis group (n=46)<br>mean ± SD | p-value |
|--------------------------|-----------|-------------------------------------|------------------------------------------|---------|
| Sagittal Cobb angle, (°) | 6 month   | -0.62±5.39                          | 1.07±7.26                                | 0.140   |
|                          | 1 year    | -1.59±6.01                          | -0.37±6.45                               | 0.288   |
|                          | 2 years   | -2.29±6.16                          | -1.35±6.25                               | 0.440   |
| Coronal Cobb angle, (°)  | 6 month   | 0.01±0.59                           | 0.13±0.91                                | 0.383   |
|                          | 1 year    | -0.23±0.60                          | -0.10±0.76                               | 0.282   |
|                          | 2 years   | -0.37±0.60                          | -0.18±0.63                               | 0.112   |

Independent-samples t-test. Data are presented as mean ± standard deviation (SD). ACDF: Anterior cervical discectomy and fusion, CDA: Cervical disc arthroplasty

This result suggests that global cervical alignment may be influenced more strongly by the natural evolution of cervical degeneration, postoperative postural adaptation, adjacent-level compensation, and baseline morphology than by the type of single-level implant alone. Recent clinical evidence has shown that CDA can maintain or improve sagittal alignment in appropriately selected patients, but this effect is not consistently superior to that of ACDF across all patient populations<sup>(18,19)</sup>.

Coronal Cobb angles decreased over time in both groups, while no significant group or group-by-time effects were observed. Because the absolute coronal angles were small at all assessments, these changes probably represented minor variations in coronal alignment rather than clinically substantial deformity correction. The comparable temporal pattern in both groups indicates that the type of anterior cervical procedure did not produce a differential effect on coronal cervical alignment in this cohort.

**Table 4.** Absolute values and changes from baseline in VAS pain score and cervical range of motion

| Clinical parameter         | Follow-up    | ACDF absolute (n=50) mean ± SD | CDA absolute (n=46) mean ± SD | p-value (absolute) | ACDF change mean ± SD | CDA change mean ± SD | p-value (change) |
|----------------------------|--------------|--------------------------------|-------------------------------|--------------------|-----------------------|----------------------|------------------|
| VAS pain score             | Preoperative | 7.2±1.3                        | 7.1±1.4                       | 0.718              |                       |                      |                  |
|                            | 6 month      | 2.9±1.2                        | 2.8±1.3                       | 0.696              | -4.3±1.7              | -4.3±1.6             | 0.912            |
|                            | 1 year       | 1.9±1.1                        | 1.8±1.1                       | 0.657              | -5.3±1.5              | -5.3±1.4             | 0.841            |
|                            | 2 years      | 1.6±1.0                        | 1.6±1.0                       | 0.984              | -5.6±1.4              | -5.5±1.5             | 0.694            |
| Total cervical ROM, (°)    | Preoperative | 295.0±28.4                     | 295.0±27.8                    | 0.998              |                       |                      |                  |
|                            | 6 month      | 251.2±30.1                     | 276.2±29.6                    | <0.001             | -43.8±24.6            | -18.8±26.1           | <0.001           |
|                            | 1 year       | 262.8±29.7                     | 280.9±28.9                    | 0.003              | -32.2±23.9            | -14.1±25.4           | <0.001           |
|                            | 2 years      | 269.4±30.2                     | 271.7±30.5                    | 0.711              | -25.6±24.3            | -23.3±27.1           | 0.623            |
| Flexion, (°)               | Preoperative | 45.0±8.1                       | 45.0±7.9                      | 0.997              |                       |                      |                  |
|                            | 6 month      | 36.7±8.3                       | 41.5±8.0                      | 0.005              | -8.3±7.0              | -3.5±7.3             | <0.001           |
|                            | 1 year       | 39.2±8.0                       | 42.7±7.8                      | 0.032              | -5.8±7.2              | -2.3±7.4             | 0.010            |
|                            | 2 years      | 40.9±8.2                       | 41.0±8.1                      | 0.952              | -4.1±7.5              | -4.0±7.8             | 0.941            |
| Extension, (°)             | Preoperative | 50.0±8.5                       | 50.0±8.3                      | 0.996              |                       |                      |                  |
|                            | 6 month      | 39.7±8.7                       | 45.7±8.5                      | <0.001             | -10.3±7.6             | -4.3±7.9             | <0.001           |
|                            | 1 year       | 42.8±8.6                       | 47.1±8.4                      | 0.015              | -7.2±7.9              | -2.9±8.1             | 0.004            |
|                            | 2 years      | 44.4±8.8                       | 44.8±8.7                      | 0.824              | -5.6±8.2              | -5.2±8.5             | 0.793            |
| Right lateral flexion, (°) | Preoperative | 35.0±7.2                       | 35.0±7.0                      | 0.998              |                       |                      |                  |
|                            | 6 month      | 27.8±7.3                       | 32.2±7.1                      | 0.004              | -7.2±6.5              | -2.8±6.8             | <0.001           |
|                            | 1 year       | 30.0±7.2                       | 32.9±7.0                      | 0.048              | -5.0±6.7              | -2.1±6.9             | 0.022            |
|                            | 2 years      | 31.4±7.3                       | 31.6±7.2                      | 0.893              | -3.6±6.8              | -3.4±7.0             | 0.874            |
| Left lateral flexion, (°)  | Preoperative | 35.0±7.1                       | 35.0±7.0                      | 0.997              |                       |                      |                  |
|                            | 6 month      | 27.8±7.2                       | 32.2±7.0                      | 0.003              | -7.2±6.4              | -2.8±6.7             | <0.001           |
|                            | 1 year       | 30.0±7.1                       | 33.0±7.0                      | 0.039              | -5.0±6.7              | -2.0±6.9             | 0.018            |
|                            | 2 years      | 31.4±7.2                       | 31.6±7.1                      | 0.892              | -3.6±6.8              | -3.4±7.1             | 0.876            |
| Right rotation, (°)        | Preoperative | 65.0±9.3                       | 65.0±9.1                      | 0.999              |                       |                      |                  |
|                            | 6 month      | 59.6±9.4                       | 62.2±9.2                      | 0.174              | -5.4±6.1              | -2.8±6.3             | 0.025            |
|                            | 1 year       | 60.7±9.3                       | 62.9±9.2                      | 0.247              | -4.3±6.3              | -2.1±6.6             | 0.066            |
|                            | 2 years      | 61.1±9.5                       | 61.3±9.4                      | 0.918              | -3.9±6.5              | -3.7±6.8             | 0.869            |
| Left rotation, (°)         | Preoperative | 65.0±9.2                       | 65.0±9.0                      | 0.998              |                       |                      |                  |
|                            | 6 month      | 59.6±9.3                       | 62.4±9.1                      | 0.140              | -5.4±6.0              | -2.6±6.2             | 0.015            |
|                            | 1 year       | 60.1±9.4                       | 62.3±9.2                      | 0.250              | -4.9±6.3              | -2.7±6.5             | 0.064            |
|                            | 2 years      | 60.2±9.5                       | 61.4±9.4                      | 0.536              | -4.8±6.5              | -3.6±6.7             | 0.322            |

Data are presented as mean ± standard deviation (SD). Absolute values represent the observed measurements at each assessment time point. Change values were calculated as the follow-up value minus the corresponding preoperative value. Between-group comparisons of absolute values and change scores were performed using independent-samples t-tests. Negative visual analog scale change values indicate pain reduction, whereas negative range of motion change values indicate reduced cervical mobility relative to baseline. Dashes indicate that change-from-baseline values are not applicable at the preoperative assessment. ACDF: Anterior cervical discectomy and fusion, CDA: Cervical disc arthroplasty, VAS: Visual analog scale

Pain scores improved markedly after surgery in both groups, and no statistically significant differences were detected in VAS changes at 6 months, 1 year, or 2 years. The longitudinal model also demonstrated a significant time effect without significant group or group-by-time effects. These findings indicate that both ACDF and CDA provided sustained pain reduction and that the pattern of pain improvement was similar over time. Neural decompression is common to both procedures and may therefore be the principal determinant of postoperative pain relief, whereas preservation or elimination of index-level motion may have a smaller effect on pain intensity during the first 2 postoperative years. Long-term randomized evidence

and recent meta-analyses have also shown substantial improvement after both procedures, although some pooled analyses have reported statistically better VAS or functional scores after CDA; these differences are not always large enough to indicate a clinically meaningful superiority<sup>(19,20)</sup>.

The most prominent between-group differences were observed in cervical mobility. Total cervical ROM decreased in both groups, but the reduction was significantly greater after ACDF at 6 months and 1 year. Similarly, early reductions in flexion, extension, bilateral lateral flexion, and bilateral rotation were smaller after CDA. These findings are consistent with the motion-preserving rationale of cervical arthroplasty. By

**Table 5.** Implant-related bone changes and heterotopic ossification severity

| Radiological finding                                | ACDF/cage group (n=50)<br>n (%) | CDA/prosthesis group (n=46)<br>n (%) | p-value |
|-----------------------------------------------------|---------------------------------|--------------------------------------|---------|
| Any implant-related bone change                     | 10 (20.0)                       | 13 (28.2)                            | 0.473   |
| Osteolysis                                          | 5 (10.0)                        | 8 (17.4)                             | 0.375   |
| Periprosthetic/anterior bone loss                   | 5 (10.0)                        | 11 (23.9)                            | 0.099   |
| Radiological findings suggestive of osteonecrosis   | 5 (10.0)                        | 5 (10.9)                             | 1.000   |
| Implant subsidence                                  | 7 (14.0)                        | 5 (10.9)                             | 0.762   |
| Implant migration                                   | 5 (10.0)                        | 2 (4.3)                              | 0.438   |
| Segmental collapse                                  | 10 (20.0)                       | 1 (2.2)                              | 0.008   |
| Revision surgery                                    | 3 (6.0)                         | 1 (2.2)                              | 0.618   |
| <b>Heterotopic ossification in CDA group, n (%)</b> |                                 |                                      |         |
| Grade 0                                             | -                               | 24 (52.2)                            | -       |
| Grade I                                             | -                               | 8 (17.4)                             | -       |
| Grade II                                            | -                               | 8 (17.4)                             | -       |
| Grade III                                           | -                               | 4 (8.7)                              | -       |
| Grade IV/functional fusion                          | -                               | 2 (4.3)                              | -       |

Data are presented as n (%). Between-group comparisons of categorical radiological findings were performed using Fisher's exact test. Heterotopic ossification grading was assessed only in the cervical disc arthroplasty (CDA)/prosthesis group and was therefore presented descriptively without a between-group comparison. ACDF: Anterior cervical discectomy and fusion

**Table 6.** Overall and time-dependent differences between the ACDF/cage and CDA/prosthesis groups

| Outcome variable          | Change over time in both groups, p-value | Overall difference between groups, p-value | Difference in change over time between groups, p-value |
|---------------------------|------------------------------------------|--------------------------------------------|--------------------------------------------------------|
| Sagittal Cobb angle       | 0.021                                    | 0.684                                      | 0.412                                                  |
| Coronal Cobb angle        | <0.001                                   | 0.573                                      | 0.286                                                  |
| VAS pain score            | <0.001                                   | 0.738                                      | 0.819                                                  |
| Total cervical ROM        | <0.001                                   | 0.036                                      | 0.004                                                  |
| Flexion ROM               | <0.001                                   | 0.041                                      | 0.012                                                  |
| Extension ROM             | <0.001                                   | 0.028                                      | 0.006                                                  |
| Right lateral flexion ROM | <0.001                                   | 0.052                                      | 0.018                                                  |
| Left lateral flexion ROM  | <0.001                                   | 0.048                                      | 0.021                                                  |
| Right rotation ROM        | 0.002                                    | 0.144                                      | 0.073                                                  |
| Left rotation ROM         | 0.003                                    | 0.131                                      | 0.086                                                  |

Longitudinal changes were analyzed using linear mixed-effects models. The first p-value indicates whether the outcome changed over time when both surgical groups were considered together. The second p-value indicates whether there was an overall difference between the ACDF/cage and CDA/prosthesis groups across all assessments. The third p-value indicates whether the pattern of change over time differed between the groups. ACDF: Anterior cervical discectomy and fusion, CDA: Cervical disc arthroplasty, VAS: Visual analog scale, ROM: Range of motion

maintaining mobility at the operated segment, CDA may reduce the immediate loss of global cervical movement associated with fusion and allow earlier restoration of functional cervical mobility. Contemporary meta-analyses have likewise reported greater postoperative ROM after CDA than after ACDF, together with lower adjacent-segment degeneration or reoperation rates in selected populations<sup>(16,19)</sup>.

The early mobility advantage of CDA was most consistent for flexion, extension, and bilateral lateral flexion. At the 1 year follow-up, differences remained significant for these movement directions, whereas rotational differences were no longer significant. This may indicate that the effect of single-level arthroplasty on global cervical mobility is direction dependent. Flexion-extension is the principal movement occurring at the subaxial cervical motion segments and is more directly influenced by index-level fusion or arthroplasty. In contrast, total cervical rotation includes a major contribution from the upper cervical spine, particularly the C1-C2 segment, potentially reducing the relative influence of a single subaxial operative level on global rotation measurements.

At 2 years, the differences in total cervical ROM and all individual movement directions were no longer statistically significant. This convergence may reflect gradual functional adaptation in the ACDF group, reduced motion of the prosthetic segment in the CDA group, or both. Patients undergoing ACDF may develop compensatory motion at non-operated cervical levels, while CDA patients may experience progressive heterotopic ossification, periprosthetic remodeling, facet degeneration, or reduction in prosthesis mobility. Although long-term meta-analyses generally demonstrate better preservation of index-level ROM after CDA, the magnitude of this advantage varies considerably among implants and patients and does not necessarily translate into a persistent difference in total clinical cervical ROM<sup>(21,22)</sup>. Because total cervical ROM was derived from the six directional measurements, the total and direction-specific ROM findings should not be interpreted as independent effects; rather, the directional analyses provide additional information regarding the movement components contributing to the overall ROM pattern.

The longitudinal models supported the point-by-point ROM findings. Significant group-by-time interactions were identified for total ROM, flexion, extension, and bilateral lateral flexion, demonstrating that the temporal pattern of recovery differed between the procedures. In contrast, the interactions for bilateral rotation did not reach statistical significance. These findings suggest that the principal effect of CDA was not simply a constant overall difference in mobility but a greater preservation of selected movement directions during early and mid-term recovery, followed by convergence between the procedures at 2 years.

Implant-related bone changes were observed in both groups. Periprosthetic or anterior bone loss was numerically more frequent in the CDA group; however, the between-group difference was not statistically significant. Bone loss adjacent

to a cervical disc prosthesis may represent several distinct processes, including adaptive stress-related remodeling, anterior vertebral resorption, implant-bone interface reactions, wear particle-induced osteolysis, infection, or altered load transfer. Therefore, radiographic anterior bone loss should not automatically be interpreted as progressive inflammatory osteolysis<sup>(8,9)</sup>.

No significant between-group differences were detected for osteolysis, radiological findings suggestive of osteonecrosis, implant subsidence, implant migration, or revision surgery. In contrast, segmental collapse was significantly more frequent in the ACDF group than in the CDA group. This difference may reflect cage-related endplate loading, subsidence-associated loss of segmental height, differences in load distribution, or variations in bone quality and surgical technique. However, because the number of events was limited and the study was retrospective, this finding should be interpreted cautiously. Potential confounding factors such as cage design, supplemental fixation, endplate preparation, preoperative disc height, and bone mineral density were not analyzed separately<sup>(23)</sup>.

Heterotopic ossification of varying severity was observed in the CDA group, including advanced ossification and functional fusion. Heterotopic ossification is an important potential limitation of CDA because progressive bone formation may restrict prosthetic motion and diminish the biomechanical distinction between arthroplasty and fusion. Implant undersizing, incomplete endplate coverage, surgical trauma, bone debris, patient-related factors, and prosthesis design have been associated with heterotopic ossification after cervical disc replacement. A recent systematic review and meta-analysis particularly emphasized the relationship between endplate coverage and heterotopic ossification development<sup>(24)</sup>.

The presence of grade 3 or 4 heterotopic ossification may partly account for the disappearance of the CDA mobility advantage by the 2 year follow-up. However, this explanation remains exploratory because the present study did not directly analyze the relationship between heterotopic ossification grade and longitudinal ROM change. Future analyses should compare late ROM among CDA patients with low-grade and high-grade heterotopic ossification and should include index-level flexion-extension radiographs to determine whether the observed reduction in global ROM corresponds to actual prosthetic segment restriction.

### Study Limitations

The findings of this study should be interpreted in light of several limitations. First, the retrospective design and non-random treatment allocation introduce the possibility of selection bias and incomplete control of factors influencing the choice between ACDF and CDA. Second, all radiological measurements were performed by a single evaluator, and intraobserver and interobserver reliability analyses were not performed. Third, total clinical cervical ROM represents global rather than index-level motion and may be influenced by

upper cervical and adjacent-segment compensation. Fourth, different cage and cervical disc prosthesis designs may have been used, and implant-specific effects could not be analyzed; implant design may influence heterotopic ossification and implant-related bone changes. Fifth, the relationship between heterotopic ossification grade and postoperative ROM was not directly analyzed; therefore, its proposed contribution to the loss of the early motion-preserving advantage of CDA remains exploratory. Finally, the relatively short 2 year follow-up period may be insufficient to determine long-term clinical and implant-related outcomes, including periprosthetic bone loss, osteolysis, adjacent-segment degeneration, and functional fusion.

## CONCLUSION

In conclusion, both single-level ACDF and CDA produced similar improvements in pain and comparable longitudinal changes in cervical Cobb angles. CDA provided better preservation of total cervical ROM, flexion, extension, and lateral flexion during early and mid-term follow-up; however, these differences were no longer evident at 2 years. Periprosthetic or anterior bone loss was numerically more frequent after CDA, whereas segmental collapse was significantly more frequent after ACDF. Heterotopic ossification, including functional fusion, occurred in a proportion of arthroplasty patients. These findings support the short- to mid-term motion-preserving effect of CDA but also indicate that this advantage may decrease over time. Larger prospective studies incorporating index-level dynamic radiographs, standardized implant-specific analyses, measurement reliability testing, and longer follow-up are required to confirm these findings.

## Ethics

**Ethics Committee Approval:** Ethical approval was obtained from the Nuh Naci Yazgan University Non-Interventional Clinical Research Ethics Committee (approval no: 2026/04-001, date: 16.04.2026). Institutional permission was granted by the Kayseri Provincial Directorate of Health, Public Hospitals Services Presidency (approval no: E-29701769-619-299456034, date: 29.12.2025) and officially communicated under letter no: E-94068515-619-299696227, date: 30.12.2025.

**Informed Consent:** As this study involved the retrospective use of patient data, the necessary institutional permission was obtained in accordance with the applicable regulations on the protection of personal data. All patient data were anonymized before analysis, and the study was conducted in accordance with the principles of the Declaration of Helsinki.

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## Footnotes

### Authorship Contributions

Surgical and Medical Practices: M.O., M.M., S.Y., Concept: M.O., Design: M.O., Data Collection or Processing: M.O., M.M., S.Y., Analysis or Interpretation: M.O., S.Y., Literature Search: M.O., M.M., S.Y., Writing: M.O., M.M., S.Y.

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## REFERENCES

- Ames CP, Blondel B, Scheer JK, Schwab FJ, Le Huec JC, Massicotte EM, et al. Cervical radiographical alignment: comprehensive assessment techniques and potential importance in cervical myelopathy. *Spine (Phila Pa 1976)*. 2013;38:S149-60.
- Smith GW, Robinson RA. The treatment of certain cervical-spine disorders by anterior removal of the intervertebral disc and interbody fusion. *J Bone Joint Surg Am*. 1958;40-A:607-24.
- Gao R, Yang L, Chen H, Liu Y, Liang L, Yuan W. Long term results of anterior corpectomy and fusion for cervical spondylotic myelopathy. *PLoS One*. 2012;7:e34811.
- Badhiwala JH, Platt A, Witiw CD, Traynelis VC. Cervical disc arthroplasty versus anterior cervical discectomy and fusion: a meta-analysis of rates of adjacent-level surgery to 7-year follow-up. *J Spine Surg*. 2020;6:217-32.
- Harrison DE, Harrison DD, Cailliet R, Troyanovich SJ, Janik TJ, Holland B. Cobb method or Harrison posterior tangent method: which to choose for lateral cervical radiographic analysis. *Spine (Phila Pa 1976)*. 2000;25:2072-8.
- Burkus JK, Traynelis VC, Haid RW, Mummaneni PV. Clinical and radiographic analysis of an artificial cervical disc: 7-year follow-up from the Prestige prospective randomized controlled clinical trial: clinical article. *J Neurosurg Spine*. 2014;21:516-28.
- Zhu Y, Zhang B, Liu H, Wu Y, Zhu Q. Cervical disc arthroplasty versus anterior cervical discectomy and fusion for incidence of symptomatic adjacent segment disease: a meta-analysis of prospective randomized controlled trials. *Spine (Phila Pa 1976)*. 2016;41:1493-502.
- Spece H, Khachatryan A, Phillips FM, Lanman TH, Andersson GBJ, Garrigues GE, et al. Clinical management of bone loss in cervical total disc arthroplasty: literature review and treatment recommendations. *Eur Spine J*. 2024;33:2969-81.
- Wahbeh JM, Park SH, Campbell P, Ebrahimzadeh E, Sangiorgio SN. The lexicon for periprosthetic bone loss versus osteolysis after cervical disc arthroplasty: a systematic review. *Eur Spine J*. 2022;31:830-42.
- Celenza A, Gaff J, Pabbruwe M, Amaya J, Amlani A, Berg A, et al. The total disc replacement osteolysis grading scale - a simple, reliable and quantifiable tool for assessing, managing and reporting osteolysis after cervical total disc replacement. *Eur Spine J*. 2026;35:1706-14.
- Formica M, Zanirato A, Cavagnaro L, Basso M, Divano S, Formica C, et al. What is the current evidence on vertebral body osteonecrosis?: a systematic review of the literature. *Asian Spine J*. 2018;12:586-99.
- Yu CW, Hsu CY, Shih TT, Chen BB, Fu CJ. Vertebral osteonecrosis: MR imaging findings and related changes on adjacent levels. *AJNR Am J Neuroradiol*. 2007;28:42-7.
- Hawker GA, Mian S, Kendzerska T, French M. Measures of adult pain: visual analog scale for pain (VAS pain), numeric rating scale for pain (NRS pain), McGill pain questionnaire (MPQ), short-form McGill pain questionnaire (SF-MPQ), chronic pain grade scale (CPGS), short form-36 bodily pain scale (SF-36 BPS), and measure of intermittent and

- constant osteoarthritis pain (ICOAP). *Arthritis Care Res (Hoboken)*. 2011;63:S240-52.
14. Huskisson EC. Measurement of pain. *Lancet*. 1974;2:1127-31.
  15. Yakdan S, Benedict B, Botterbush K, Lagisetty A, Kaleem MI, Alessio R, et al. Randomized controlled trials comparing cervical disc arthroplasty and anterior cervical discectomy and fusion outcomes in degenerative spine disease: a systematic review and meta-analysis. *J Neurosurg Spine*. 2025;43:703-16.
  16. Zavras AG, Acosta JR, Holmberg KJ, Semenza NC, Jayamohan HR, Cheng BC, et al. Effect of device constraint: a comparative network meta-analysis of ACDF and cervical disc arthroplasty. *Spine J*. 2024;24:1858-71.
  17. Katsuura Y, York PJ, Goto R, Yang J, Vaishnav AS, McAnany S, et al. Sagittal reconstruction and clinical outcome using traditional ACDF, versus stand-alone ACDF versus TDR: a systematic review and quantitative analysis. *Spine (Phila Pa 1976)*. 2019;44:E1151-8.
  18. Pouleau HB, De Witte O, Dhaene B, Jodaitis A. Restore cervical sagittal alignment by cervical disc arthroplasty and systematic total bilateral unicusctomy in severe spondylosis: a prospective study. *Brain Spine*. 2023;3:101765.
  19. Zhang Y, Ju J, Wu J. Comparison of cervical disc arthroplasty versus anterior cervical discectomy and fusion for the treatment of single-segment cervical degenerative disc disease with a minimum of 4-year follow-up: a systematic review and meta-analysis of randomized controlled trials. *J Orthop Surg Res*. 2025;20:758.
  20. Quinto ES, Paisner ND, Huish EG, Senegor M. Ten-year outcomes of cervical disc arthroplasty versus anterior cervical discectomy and fusion: a systematic review with meta-analysis. *Spine (Phila Pa 1976)*. 2024;49:463-9.
  21. Qi M, Xu C, Liu Y, Cao P, Wang X, Chen H, et al. Comparison of clinical outcomes between cervical disc arthroplasty and anterior cervical discectomy and fusion for the treatment of single-level cervical spondylosis: a 10-year follow-up study. *Spine J*. 2023;23:361-8.
  22. Zhang Y, Lv N, He F, Pi B, Liu H, Chen AC, et al. Comparison of cervical disc arthroplasty and anterior cervical discectomy and fusion for the treatment of cervical disc degenerative diseases on the basis of more than 60 months of follow-up: a systematic review and meta-analysis. *BMC Neurol*. 2020;20:143.
  23. Häckel S, Gaff J, Pabbruwe M, Celenza A, Kern M, Taylor P, et al. Heterotopic ossification, osteolysis and implant failure following cervical total disc replacement with the M6-C™ artificial disc. *Eur Spine J*. 2024;33:1292-9.
  24. Kazarian GS, Cecere R, Sheha E, Dowdell J, Iyer S, Qureshi S. The impact of endplate coverage on heterotopic ossification following cervical disc replacement: a systematic review and meta analysis. *Spine (Phila Pa 1976)*. 2024;49:1445-55.